# Mechanistic-Empirical Equivalent Single Axle Loads For Urban Pavements

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ABSTRACT

The deregulation of the trucking industry in the mid-1980's resulted in the growth of commercial vehicles not only in number, but also in weight, size and dimension. As a result, road agencies are finding their road networks being subjected to commercial vehicle load spectra greater than those initially projected. The augmented load spectra, combined with the aged state of many in-service roads, are resulting in the accelerated deterioration of our roadway infrastructure.

Although much empirical evidence exists regarding the performance of rural pavements subjected to various types of loading, there is a lack of knowledge regarding the operation of commercial vehicles within the urban environment and their ensuing effects on urban roads. Urban municipalities are therefore beginning to realize the importance of identifying and quantifying the effects of commercial vehicle operations (CVO) on urban road assets, traffic congestion and motorist safety.

Due to the limitations of conventional Equivalent Single Axle Loads (ESALs) when applied to urban pavements, this research aimed to investigate commercial vehicle load equivalencies for various classes of urban roadway in the City of Saskatoon. Urban load equivalencies were created by combining a traffic load spectra from a typical freeway in the City of Saskatoon with structural deformation and damage responses measured across several urban roadways. This established a framework for calculating the responses incurred from commercial vehicle loading across different types of urban roads.

Based on the results of the mechanistic-empirical urban load equivalency analysis performed in this research, urban ESAL factors (ESALFs) for local-industrial roadways were found to range from 50 percent less than to 250 percent greater than conventional load equivalencies. Urban arterial ESALFs ranged from 20 percent to 260 percent greater than

conventional load equivalencies. The primary response-based ESALFs for urban local and collector roadways ranged from 150 to 700 percent greater than conventional load equivalencies.

The large range in mechanistic-empirical ESALFs across urban road classes indicated that typical urban roadways are much more sensitive to heavy vehicle loads than their rural highway counterparts. In a test urban traffic application, it was calculated that a typical low floor transit vehicle was capable of producing loads ranging from a minimum of nine ESALs on urban local-industrial roadways to a maximum of 140 ESALs on urban local and collector roadways.

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LIST OF ABBREVIATIONS

Abbreviation

| | |
|---|---|
| AADT | - Annual Average Daily Traffic |
| AASHO | - American Association of State Highway Officials |
| AASHTO | - American Association of State Highway and Transportation Officials |
| AVC | - Automated Vehicle Classifier |
| BP | - Bending Plate |
| CL | - Curb Lane |
| COS | - City of Saskatoon |
| CV | - Coefficient of Variance |
| CVISN | - Commercial Vehicle Information System and Networks |
| CVO | - Commercial Vehicle Operations |
| DOT | - Department of Transportation |
| EB | - Eastbound Direction of Travel |
| ESAL | - Equivalent Single Axle Load |
| ESALF | - Equivalent Single Axle Load Factor |
| GAWR | - Gross Axle Weight Rating |
| GPR | - Ground Penetrating Radar |
| GVW | - Gross Vehicle Weight |
| GVWR | - Gross Vehicle Weight Rating |
| HWD | - Heavy Weight Deflectometer |
| IRI | - International Roughness Index |
| ITS | - Intelligent Transportation Systems |
| MHTTIS | - Manitoba Highway and Truck Traffic Information System |
| ML | - Median Lane |

| | |
|---|---|
| NDT | - Non-Destructive Deflection Testing |
| PSI | - Pavement Serviceability Index |
| SDHT | - Saskatchewan Department of Highways and Transportation (now known as the Ministry of Highways and Infrastructure) |
| SI | - Structural Index |
| SLC | - Single Load Cell |
| TAC | - Transportation Association of Canada |
| tpd | - Trucks per Day |
| TRB | - Transportation Research Board |
| UMTIG | - University of Manitoba Transportation Information Group |
| VWIM | - Video Weigh-in-Motion |
| vpd | - Vehicles per Day |
| WB | - Westbound Direction of Travel |
| WIM | - Weigh-in-Motion |

DEFINITIONS

Definitions

| | |
|---|---|
| Arterial: | The third highest functional classification of roadway beneath Expressway and Freeway. Traffic volumes typically range from 5,000 vpd to 30,000 vpd with minor to rigid access control (TAC 1999). |
| Collector: | The second lowest functional classification of roadway, above local, but below Arterial, Expressway and Freeway. Traffic Volumes typically range from 5,000 vpd to 12,000 vpd (TAC 1999). |
| Expressway: | The second highest functional classification of roadway beneath Freeway. Traffic volumes are typically greater than 10,000 vpd and traffic flow is uninterrupted except at traffic signals (TAC 1999). |
| Freeway: | The highest functional classification of roadway. Traffic volumes are typically greater than 20,000 vpd and traffic is freeflow with all intersections being grade-separated (TAC 1999). |
| Local: | The lowest functional classification of urban roadway for residential areas. Traffic volumes may be upwards of 3,000 vpd and design speeds typically range from 30 km/h to 50 km/h (TAC 1999). |

Local-Industrial: The lowest classification of urban roadway for industrial areas. Traffic volumes may be upwards of 3,000 vpd and design speeds typically range from 30 km/h to 50 km/h (TAC 1999).

Pavement Serviceability: An index of pavement performance that includes functional performance relating to user service and structural performance relating to physical condition (AASHTO 1993). The Pavement Serviceability Index (PSI) is a typical measure of pavement serviceability and ranges from 0 (low) to 5 (high).

PSIPave Structural Index: A proprietary measurement of pavement structure strength developed by Pavement Scientific International Inc. for the City of Saskatoon asset management program. The index incorporates several measures of pavement structure serviceability, including but not limited to deflection, substructural deformation and strain-hardening/weakening.

Structural Number: A number representing the pavement structural stength required for a given combination of soil support, total traffic expressed in equivalent 18-kip single axle loads, terminal serviceability and environment (AASHTO 1993).

Terminal Serviceability: The lowest acceptable serviceability index before roadway resurfacing or reconstruction is necessary. The lowest acceptable index prior to reconstruction is typically 2.5 for highways and 2.0

for roadways with a classification lower than a highway (AASHTO 1993).

Thickness Index: A relationship of material layer thickness derived from 0.44 surface thickness plus 0.14 base thickness plus 0.11 subbase thickness (AASHTO 1993).

# CHAPTER 1 - INTRODUCTION

The number of commercial vehicles operating in Saskatchewan and throughout North America has significantly increased over the past decade (Morris 2003; SDHT 2005). Commercial vehicles have not only grown in number, but also in weight and size. This is primarily due to economic growth and the deregulation of the trucking industry in the mid-1980's (Hajek and Billing 2002; Berthelot et al. 2000). Although considerable empirical evidence exists regarding the effectiveness of weight enforcement initiatives on rural roadways, there is a lack of knowledge regarding urban commercial vehicle operations (CVO), as well as the impact of CVO on urban roadways (Bushman and Berthelot, 2003). As a result, transportation literature contains few studies focusing on the impact of commercial vehicle loading on urban roads, with little to no information regarding weight enforcement within urban jurisdictions.

Both urban and rural road agencies are being subjected to commercial vehicle loads that are much greater than those initially projected, causing roadways to deteriorate at an accelerated rate (Rodier et al. 2006). As such, there is a growing realization of the importance of properly and efficiently quantifying the effects of commercial vehicles on urban roadway asset life, traffic congestion, and safety, as illustrated in recent studies in the District of Columbia (Washington) and the City of New York (U.S. Department of Transportation 2004; City of New York 2006).

Previous studies have suggested that the effectiveness of truck enforcement is related to enforcement visibility and penalties associated with overloading as perceived by carriers (Paxson and Glickert 1982; Bushman and Berthelot 2003). These observations are typically based on rural enforcement programs. Therefore, taking into account the lack of CVO enforcement within urban jurisdictions, it may be hypothesized that the occurrences of commercial vehicle overloading are much more frequent in an urban setting than in a rural setting. The lack of urban CVO enforcement visibility, combined with larger commercial vehicles, increasing truck traffic volumes and the incentive to overload trucks for economic benefits (Paxson and Glickert 1982), has lead to premature deterioration of urban road networks.

Recent research has investigated mechanistic behaviour of flexible pavements in an effort to more accurately quantify and predict the actual performance of typical urban road materials and structures under diverse field state conditions (Berthelot et al. 1999). To date, this research has shown that typical road materials can be highly sensitive to induced shear stress states and rates of loading (Berthelot et al. 1999). This is critical in terms of asphaltic pavement performance in that observed traffic patterns on urban roadways tend to operate under reduced speeds, with frequent stop-and-go conditions and high density corridors utilized for commercial haul routes. As a result, the damages inflicted by commercial vehicle load spectra, whether overloaded or of legal weight, may appear much more quickly in an urban environment than in a rural environment (Berthelot et al. 1999).

The City of Saskatoon has evolved as the economic and transportation hub of the province of Saskatchewan due to its geographical location and the development of the provincial heavy industry (Berthelot et al. 2005). Consequently, truck traffic traveling through Saskatoon's commercial corridors has grown over the past decade. This has subsequently forced the City to expand its primary and secondary truck routes in an effort to meet the increasing needs of the trucking industry (Berthelot et al. 2005). The expanding urban road network, combined with increasing transport demands, has caused a growing deficit between the City's roadway maintenance requirements and its maintenance capabilities. As a result, the preventative maintenance requirements of the urban truck routes are often ignored while financing is focused on other major infrastructure projects.

In recognition of the need for reliable commercial traffic data in urban areas, a study quantifying commercial truck traffic movements and loading trends was undertaken in Saskatoon (Bushman and Berthelot 2003). The study employed a new pilot Video Weigh-in-Motion (VWIM) system that was installed across two northbound lanes of a four-lane freeway (Circle Drive at Taylor Street), located on a primary truck route through the City of Saskatoon. The Annual Average Daily Traffic (AADT) was recorded to be approximately 64,000 vehicles per day (vpd) through this corridor (City of Saskatoon 2005). The Circle/Taylor VWIM system consisted of single load cell (SLC) WIM scales in the northbound curb lane accompanied by a quartz axle sensor array in the northbound median lane. A video capture system was installed alongside the roadway to obtain side images of the passing vehicles, which were referenced and recorded alongside the corresponding WIM weight record of a vehicle. The entire system was controlled remotely in real-time via online access through a protected website.

Data was collected using the Circle/Taylor VWIM system for a period of six days in September 2002 (Bushman and Berthelot 2003). Analysis of this data indicated distinctive commercial vehicle loading patterns across the site. Vehicle classes most likely to violate legal weight limits were identified (Bushman and Berthelot 2003). The analysis found that seven and eight axle combination units represented approximately 20 percent of the total truck population, as did the smaller two and three axle trucks (Bushman and Berthelot 2003). Five and six axle semi-trailers represented nearly 60 percent of the total truck population (Bushman and Berthelot 2003). The total ESALs contributed by each vehicle class over the six day study period were

2,650 ESALs for seven and eight axle units, 3,000 ESALs for five and six axle units, and 619 ESALs for all other groups, consisting primarily of the two and three axle straight trucks (Bushman and Berthelot 2003). However, the total overweight ESALs contributed by each of the above groups were 136 ESALs, 128 ESALs and 128 ESALs for groups of seven and eight axle units, five and six axle units, and the two and three axle units (Bushman and Berthelot 2003). This indicated that, despite contributing the least to the total truck population, the smaller two and three axle straight trucks contributed a large portion of overloading per vehicle (Bushman and Berthelot 2003).

The results of the 2002 Saskatoon study held a pivotal role in verifying the need for urban municipalities to quantify, monitor and enforce CVO for effective management of their roadway assets (Bushman and Berthelot 2003). The relatively high proportion of overload ESALs from the two and three-axle straight trucks were identified as an additional concern because smaller trucks often operate on the lower class, non-structural streets, whereas larger combination units operate primarily on heavier pavement structures. However, the ESALs identified by Bushman and Berthelot (2003) may not entirely reflect the actual damage caused to non-primary urban roadways by commercial vehicles. This is because ESALs are traditionally calibrated to the effects of truck loadings at highway speeds on roadways comprised of thicker structures and little to no ‘stop and go’ conditions.

Recognizing the value of the pilot VWIM system for advanced and semi-automated urban enforcement, the City of Saskatoon installed two additional VWIM systems across all lanes of Circle Drive at a location further north of the original pilot system (Circle/Preston VWIM).

## 1.1 Research Objective

The goal of this research is to improve urban traffic management strategies for urban roadway asset management. The research objective is to combine Weigh-in-Motion with non-destructive roadway testing methods to generate a framework for calculating relative damage factors due to commercial truck loading across different classes of urban roadways.

## 1.2 Research Scope

The scope of this research includes the use of a VWIM system with integrated video capture technology located across all lanes on Circle Drive using the Circle/Preston VWIM system in Saskatoon, Canada. The Circle/Preston VWIM system is located between the Circle Drive Bridge and the Preston Avenue/Attridge Drive Overpass in Saskatoon, Saskatchewan, as illustrated in Figure 1.1. The system consists of four lanes; two northbound and two southbound. ASTM Type I WIM systems were installed in all four lanes. These consisted of bending plates (two per lane for a total of eight), and loop arrays prior to and after the bending plates in each lane to measure axle group and overall vehicle length.

The video capture system included two side-imaging cameras and two license plate cameras. The side-image cameras were installed in the ditches on either side of the roadway and were triggered by vehicles in both the curb and median lanes for the specific direction of travel. The license plate cameras were only installed over the curb lanes of each direction of travel and were triggered only by vehicles traveling in that lane. Images recorded by the cameras were linked with their corresponding WIM vehicle record through the on-site system electronics.

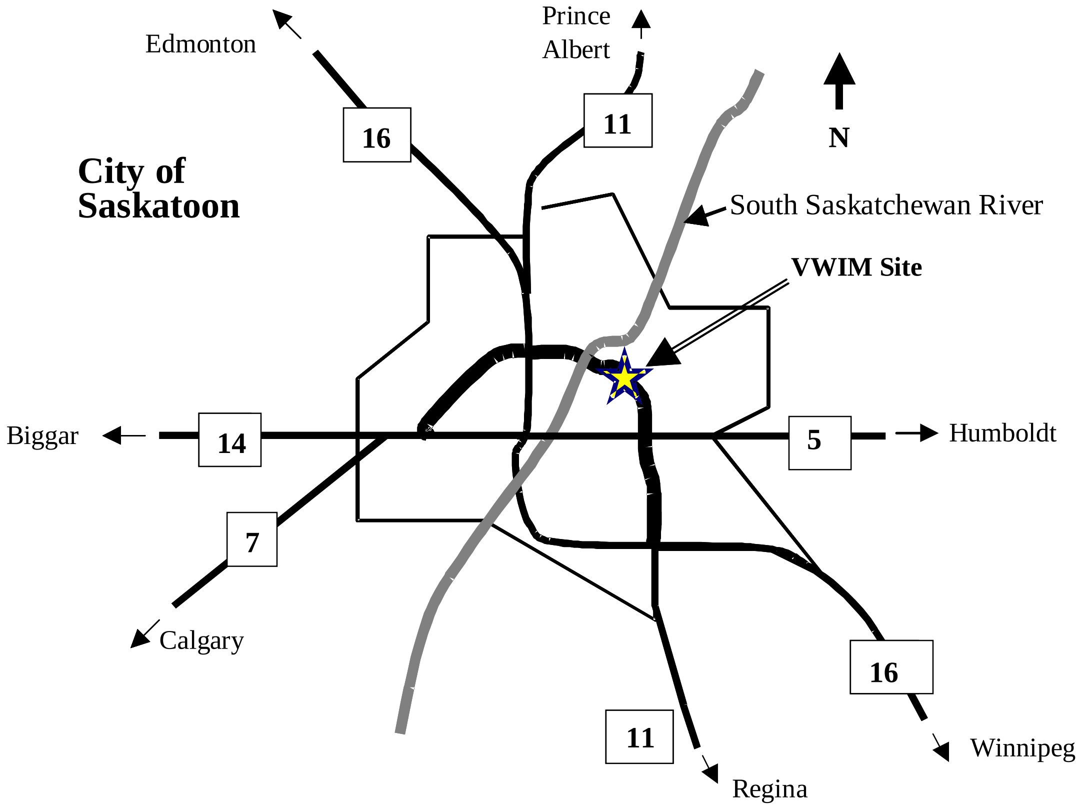


**Figure 1.1 - VWIM Site Location, Saskatoon, Saskatchewan**

This study included calibration of the VWIM System according to ASTM 1318-02 standards, as well as a validation of the system reliability. Validation of the reliability of the VWIM system using five common commercial vehicle types (Bushman and Berthelot 2003) was performed in the curb lanes only. This ensured that identification of the validation vehicle could be confirmed visually through both side-fire and license plate images.

The truck load spectra at the Circle/Preston site were quantified using the VWIM system. Heavy Weight Deflectometer (HWD) and Ground Penetrating Radar (GPR) testing was performed on different urban road classes in the City of Saskatoon. These methods were used to characterize typical pavement primary responses across load spectra ranging from secondary weights to primary plus 50 percent weights. The effects of truck loads on the different urban road types were evaluated and ESALFs were calculated for different classes of urban roads. Mechanistic-empirical ESAL tables for typical urban roads in the City of Saskatoon were then created

### .1.3 Research Methodology

The first element of this research included a background and literature review of CVO trends, WIM technologies and applications, pavement management and load spectra monitoring. The second element of this research included the calibration and validation of the Circle/Preston VWIM system according to ASTM standards. The third element of this research involved the collection of weight data from the VWIM system for seven consecutive days in order to quantify the commercial vehicle load spectra within the City of Saskatoon. The fourth element of this research involved the development of ratio relationships of pavement-load response testing on a major freeway/expressway and other urban road classes. This was required to develop a framework for calculating ESALFs reflective of different urban road classes. A comparison of two methods of generating urban ESALFs was completed and urban ESAL design tables were generated for each road class.

## 1.4 Layout of Thesis

Chapter 1 provides an introduction to the work included in this research, as well as the significance of the research to urban roadway structural asset management. This section also includes the goal, objectives, scope and methodology of the work and the layout of the thesis.

Chapter 2 summarizes the background information and literature review completed for issues relevant to this thesis, including: the effects of CVO monitoring and enforcement, empirical and mechanistic links between vehicle loads and roadway damage, rural and urban CVO trends and a review of the applications of WIM technology.

Chapter 3 summarizes the results of the calibration of the VWIM system. A detailed validation of the reliability of the commercial vehicle data collected using the system is included.

Chapter 4 quantifies the commercial vehicle load spectra within the City of Saskatoon as obtained using the Circle/Preston VWIM system.

Chapter 5 assesses the ESAL spectra generated by the Circle/Preston VWIM system and its effects on typical urban roads through the use of HWD and GPR surveys on road structures in Saskatoon. This chapter utilizes the aforementioned non-destructive mechanistic-based pavement testing methods to generate ratio-based urban ESALFs for the various urban road classes within the City of Saskatoon.

Chapter 6 presents an application of the mechanistic-empirical ESALFs derived in this study through the generation of urban load equivalency tables by urban road class.

Chapter 7 presents the summary, conclusions, recommendations and a discussion of possible future research that would build on the results of this study.

# CHAPTER 2 - BACKGROUND AND LITERATURE REVIEW

The deterioration of a roadway is accelerated over time by the repeated application of loads generated by heavy vehicles. Research has shown that pavement damage can be more than doubled by axle loads that are only 20 percent over the permitted maximum (World Road Association 2004). The growth in truck traffic volumes as observed over the past few decades, combined with increasing commercial vehicle weights and dimensions, is causing the anticipated lifespan of many roadways to decrease. Consequently projected maintenance and preservation costs increase (SDHT 2005). Pavement deterioration is further intensified by an incentive for overweight trucks due to economic benefits of an increased payload (Cunagin et al. 1997; Paxson and Glickert 1982).

Faced with the decreasing lifespan of their infrastructure, roadway agencies are investigating low-cost but effective methods of CVO monitoring and enforcement. In an effort to control the occurrences of overloading and to extend the lifespan of its roadway infrastructure, the Saskatchewan Department of Highways and Transportation has attempted to gain a thorough understanding of the commercial vehicle load spectra. Investigations of the use of Weigh-in-Motion (WIM) technology for traffic data collection and commercial vehicle enforcement in rural applications were conducted (SDHT 2005). However, urban municipalities have not yet widely implemented weight monitoring programs specifically designed to study and enforce the preservation of their infrastructure (Bushman and Berthelot 2003).

Although much empirical evidence exists regarding weight enforcement on rural pavements, little work has been done to specifically target the design and maintenance issues of urban infrastructure assets (Bushman and Berthelot 2003). Recent research investigating the mechanistic behaviour of typical flexible pavement materials shows that their performance-related behaviour can be highly sensitive to induced multi-axial stress, as well as the rate of loading (Berthelot et al. 1999). Consequently, damage may appear more quickly on urban pavements in comparison with rural pavements due to restricted speeds, frequent stop and go conditions, and increased traffic volumes on main corridors within urban jurisdictions (Bushman and Berthelot 2003). Given the sensitivity of roadway performance to urban truck traffic, it is clear that urban municipalities need to monitor CVO more diligently for effective roadway structural asset management.

## 2.1 Analyzing Changing Truck Load Spectra Trends

The size of commercial truck traffic on many urban roadways has been steadily increasing over recent years, as is evident by the increased dimensions of commercial vehicles currently in operation shown in Figure 2.1. Based on figures reported by the Transportation Research Board's (TRB) Committee for the Study of Freight Capacity for the Next Century, commercial traffic volumes are projected to increase by 40 percent by the year 2020 (TRB Special Report 271 2003). Since most shipment destinations and origins are concentrated within urban centres, the projected increase in commercial traffic will further aggravate passenger vehicle versus freight conflicts within urban infrastructure (TRB Special Report 271 2003).


**Figure 2.1- 12 Axle Truck from Federated Co-Operatives Ltd. (C. Berthelot 2005)**

According to traffic statistics provided by the Saskatchewan Department of Highways and Transportation, the total ESALs on Saskatchewan highways in 2004 was approximately four billion per year cumulative over the entire 23,000 km highway system (SDHT 2005). Historical records show that the truck population on Saskatchewan highways has increased by more than 47 percent over the past ten years and that trade with the United States nearly doubled during that same timeframe (SDHT 2005). Specialized carrier requirements and increased commercial vehicle demands are occurring due to the abandonment of rail branch lines, continued growth in the oil, gas, forestry and mining industries, as well as the provincial tourism sector. These increases are being reflected on provincial roadways (SDHT 2005).

Though steadily increasing over the past decade, the most significant increase in truck traffic occurred towards the end of the 1990's, as documented in a 2002 study analyzing changes in American trucking trends (Hajek and Billing 2002). This study indicated an overall increase from a 3.4 percent annual growth rate to 5.8 percent. They observed that the largest increase in commercial vehicle annual growth rate occurred on urban freeways (6.5 percent). Hajek and

Billing (2002) concluded that the trend of increasing truck size and frequency could be related to: advancements in macro economics, such as globalization of the economy; changes to trucking policies, such as the deregulation of the trucking industry; and advancements in engineering technology that improve the efficiency of transport, such as the increased use of air suspension systems.

Hajek and Billing (2002) predicted that it would be possible to mitigate the occurrence of rapid growth in truck volumes in the future. However, they also note that the trend of increasing truck size and weights, as well as the increasing number of axles included within axle groupings, would continue due to economies of scale of larger trucks and the influence of NAFTA on national and global trade.

Traditional weight monitoring and enforcement efforts using static weigh stations on rural highways are not capable of generating total commercial vehicle weight compliance due to issues with weigh station evasion and/or truck route efficiency and selection (Cunagin et al. 1997). A study conducted for the Florida Department of Transportation (FDOT) in the late 1990's found that the occurrences of weigh station avoidance by overweight trucks was much greater than initially presumed by FDOT personnel (Cunagin et al. 1997). Based on data gathered from two permanent weigh stations and four bypass routes (monitored using WIM), 19 percent of the trucks observed bypassing the weigh stations were overweight, whereas only 0.8 percent were overweight at the fixed locations (Cunagin et al. 1997). Static weigh station avoidance combined with the lack of commercial vehicle monitoring and thinner pavement structures in urban jurisdictions creates an environment more conducive to frequent and severe pavement damage due to truck loading.

The Saskatchewan Department of Highways and Transportation (SDHT) initiated partnership opportunities with large-scale commercial carriers in an effort to compensate highway infrastructure for accelerated rural road damages and increased maintenance requirements due to commercial trucking (Berthelot et al. 2000). The transportation partnership programs encourage increased economic productivity by reducing transportation costs through the use of vehicles that may exceed regulated weights and/or dimensions (SDHT 2007). In turn, the commercial vehicle partners are obliged to pay for incremental damages inflicted to the provincial roadway infrastructure (SDHT 2007). The partnership payments are incorporated into a specialized fund dedicated to improving trucking-related infrastructure throughout the province (SDHT 2007).

As a result of the trucking partnership initiatives, the management of road maintenance initiatives may be streamlined to operate concurrently with commercial transport. However, difficulties have been encountered in efforts to quantitatively analyze incremental pavement damage due to the empirical methods currently used to assess roadway performance (Berthelot et al. 2000). As a result, the fees charged for specialized overweight permits often do not reflect the cost of the additional roadway damage (Paxson and Glickert 1982). This is particularly evident in climates facilitating seasonally-variable damages, where studies have shown that the resilient modulus of asphalt may vary drastically in sub-zero temperatures (Watson and Rajapakse 2000). Also, these fees are typically not shared with urban jurisdictions to help alleviate the additional cost of the damage caused by the permitted overweight vehicles. Therefore a gap is created regarding compensation for elevated damages to the urban roadway infrastructure incurred through trucking partnership programs.

In response to the lack of knowledge regarding CVO within urban jurisdictions, the District of Columbia (Washington) recently commissioned a study to develop a comprehensive urban truck management strategy (U.S. Department of Transportation 2004). This study quantified existing trucking conditions throughout the District in order to generate recommendations for a road infrastructure management strategy that would streamline existing and proposed truck routes, reduce congestion and improve motorist safety (U.S. Department of Transportation 2004). The City of New York is also conducting a study to assess truck management strategies that may reduce the impacts of truck traffic on urban roadway networks (City of New York 2006). Though still in progress, the initial recommendations of the study have cited a need for urban truck enforcement (City of New York 2006). However, the focus of the enforcement strategy remains solely on the issues of truck routes and parking (City of New York 2006), with little mention of weight monitoring, enforcement and roadway impact assessment.

## 2.2 Mechanistic and Empirical Modeling of Loading and Pavement Performance

In order to determine the relationship between pavement performance and repeated commercial truck loadings, the American Association of State Highway Officials (AASHO) undertook a series of roadway tests in the late 1950's. Five specific goals were identified for the purpose of the testing, including (Highway Research Board 61A 1961):

- Determining the relationship between the repetition of axle loads (of different magnitudes and arrangements) and the performance of roadway structures, and;
- Developing a method of performance evaluation that could be used to determine the load-carrying capacity of roadways.

Three vehicle types were used for accelerated pavement damage simulation testing: a 2-axle straight truck; a 5-axle tractor-semi truck; and a 3-axle straight truck. The single axle loads ranged from 907 kg (2,000 lb) to 13,608 kg (30,000 lb), and the tandem axle loads ranged from 10,886 kg (24,000 lb) to 21,772 kg (48,000 lb) (Highway Research Board 61A 1961). Trucks were driven on a series of loop-shaped test tracks at an operational speed of approximately 56 km/h (35 mph) whenever possible (Highway Research Board 61G 1961) and constant tire pressure was maintained between 515 kPa and 550 kPa **(**Wang and Machemehl 2006**)**.

This work led to the development of the Pavement Serviceability Index (PSI) and ESALs. Based on the performance relationships derived from the roadway structural serviceability and roughness ratings, the concept of PSI was developed. As illustrated below, PSI accounts for roadway slope variance, rut depth, surface cracking and patching (Robert et al. 2000). It was found that a typical new pavement structure should have a PSI rating of between four and five, and that pavement repair was typically required when the PSI value reached between 1.5 and 2.5.

$$PSI = 5.03 - 1.91 \log (1 + SV) - 1.38\, RD^2 - 0.01\, (C + P)^{1/2} \qquad [2.1]$$

Where: SV = slope variance (%);

RD = rut depth (inches);

C = cracking (feet per 1,000 square feet), and;

P = patching (square feet per 1,000 square feet).

It was concluded that a test pavement with a thickness index slightly less than four could withstand 1,000,000 applications of an 8,165 kg (18,000 lb) single axle load before its serviceability decreased to 2.5 (Highway Research Board 61G 1961). It was concluded that the effects of any load on pavement performance could be represented by the number of single applications of an 8,165 kg (18,000 lb) single axle load (Garber and Hoel 1999).

From the research results obtained during the AASHO road tests, ESALF tables were created to group truck loads into repetitions of a standardized comparable load (single axle load) that would facilitate simplistic pavement design calculations and would not require the accumulation of different damage rates for specific distress types (Lu and Harvey 2006). Since tridem axle configurations were not utilized at the time of the initial road tests, ESALF relationships for tridem axles were generated through similar research completed after the initial road tests (AASHTO 1993). As per the load-pavement damage relationships, the AASHO load equivalency factors displayed a tendency to increase as an approximate function of the ratio of any given load to the standard 18,000 lb load raised to the fourth power (AASHTO 1993, Timm et al. 2006). This indicated that pavement damage, representing a decrease in pavement life, increases exponentially with increasing truck loads, as illustrated in Figure 2.2.

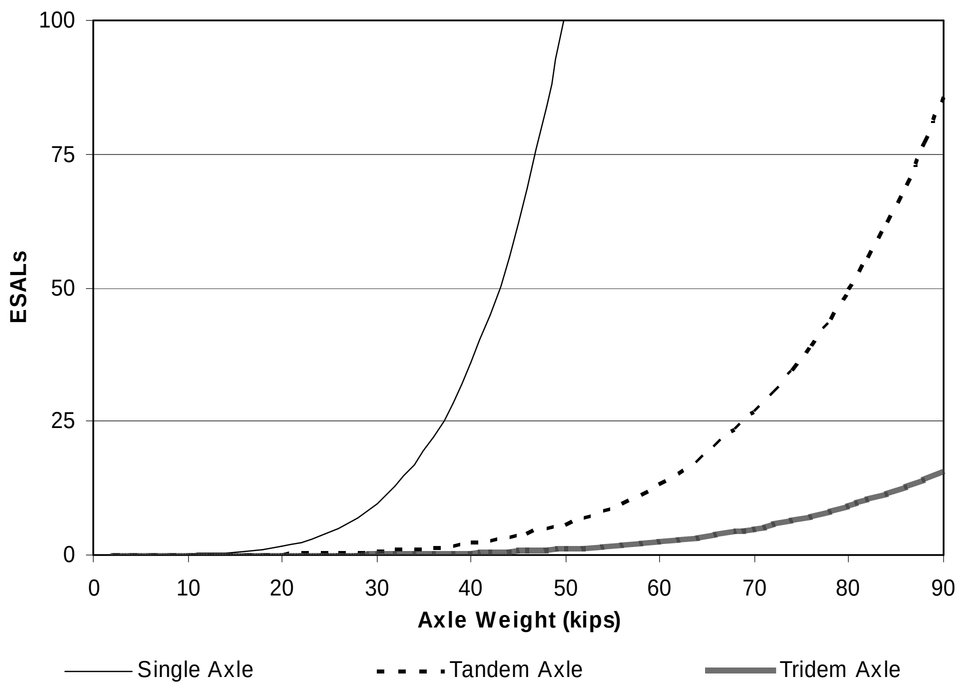


**Figure 2.2 – ESAL vs. Truck Load AASHTO Relationship**

The load equivalency factors developed by AASHTO were based on observations from the Ottawa, Illinois road tests (AASHTO 1993). As such, AASHTO load equivalencies have limitations due to restricted load magnitude and application frequency, simplified test pavements, and lack of consideration for pavement age and environment (Berthelot et al. 2000, AASHTO 1993). The AASHTO design equation for flexible pavements does not consider variance within tire characteristics, such as air pressure, size and vehicle suspension types (TRB Report No. 227 1990, Wang and Machemehl 2006). Also, due to the accelerated nature of the AASHO road tests, the effects of randomness in the placement of vehicles within and beyond lane boundaries was not considered (TRB Report No. 225 1990), nor were the effects of environmental loading on pavement life. Given the varying types of pavement structures throughout provincial jurisdictions, as well as increasing truck weights and dimensions, the structural behaviour of roadways may be best-suited by non-linear trends that deviate from traditional empirically-based load equivalencies (Berthelot et al. 2000).

Seven distress models can be applied to roadway deterioration (Roberts et al. 2000) based on the definitions of distress for flexible pavement, as proposed by Kennedy et al. (1979):

- Load-associated cracking;
- Non-load associated cracking;
- Reflection cracking, caused by discontinuities in underlying structural layers;
- Distortion (including shoving, rutting and slippage);
- Disintegration of the pavement structure, characterized by ravelling, wear loss, stripping and the development of potholes;
- Reduced skid resistance, and;
- Roughness of the overlying asphalt layer.

Pavement distresses can cause pavement structures to deteriorate at an accelerated rate over time and are typically propagated by the following factors (TRB Special Report No. 227, TRB Special Report No. 225, Berthelot et al. 2000, Watson and Rajapakse 2000):

- Traffic loadings, particularly the repeated passing of heavy vehicles.
- Vehicle characteristics, such as tire characteristics (pressure, size, spacing), suspension systems, and axle spacing.
- Climate and environmental loadings, such as freeze-thaw climate cycles.
- Pavement structure and layer thickness.
- Prior existing pavement distresses.
- Pavement structural materials and subgrade characteristics.
- Roadway geometric design.
- Construction quality practices.
- Distress and preventative maintenance practices.

For example, in the central provinces of Canada where temperatures may range drastically from the winter to the summer months, freeze-thaw cycles have a great effect on a pavement's ability to carry traffic loads without incurring damage (Watson and Rajapakse 2000). During the colder winter months, the granular base, subbase and subgrade layers of a roadway structure are typically frozen, resulting in a higher stiffness with a greater load-bearing capacity (Watson and Rajapakse 2000). However, upon spring thaw, granular layers of a structure may reach near-saturation, causing the load carrying ability of a pavement to drastically decrease (Watson and Rajapakse 2000). As a result, spring load restrictions are typically imposed in regions prone to freeze-thaw cycles to mitigate the occurrence of roadway failure due to repetitive heavy traffic loads (Watson and Rajapakse 2000).

The accelerated nature of the initial AASHO road tests excluded the consideration of various elements shown to facilitate the propagation of pavement damage. Consequently, single axle load equivalencies do not accurately reflect the actual damage caused to pavement structures by repeated traffic loadings. This is particularly evident in the response of urban roadways to traffic loads, since pavement damage and subsequent roadway deterioration typically propagate sooner and more quickly within an urban environment than in a rural environment (Bushman and Berthelot 2003). This heightened sensitivity to deformation occurs primarily because urban roadways generally consist of thinner structures than their rural counterparts. They are also subjected to slower loading patterns with more frequent 'stop n' go' conditions, as well as repeated turning movements (Bushman and Berthelot 2003).

### 2.3 Using WIM to Preserve Infrastructure

CVO trends have become a major agency focus as emphasis has shifted from the construction of roadways to their maintenance and preservation. WIM technology has traditionally been used for data collection initiatives aimed at quantifying loading trends and vehicle behaviour for design and planning purposes (Zhi et al. 1999). WIM is the process by which the dynamic forces of a moving vehicle transmitted onto a pavement through tire-contact points are measured and the corresponding static gross vehicle weight is estimated (Andrle et al. 2002). As per ASTM 1318-02, there are currently three types of WIM technology available and one type pending development:

- WIM Type I is designed to be used in one or more lanes of traffic for data collection and is capable of accommodating highway vehicles moving at speeds ranging from

16 km/h to 130 km/h. Type I WIM systems use bending plate-type technology which, based on ASTM accuracy requirements, are the second-most accurate WIM technology.

- WIM Type II is also designed to be used in one or more lanes of traffic for data collection and is capable of accommodating highway vehicles moving at speeds ranging from 24 km/h to 130 km/h. Type II WIM uses piezoelectric and quartz sensor technology and is the third-most accurate WIM technology.
- WIM Type III is designed to be used in one or more lanes of traffic for data collection and/or weight enforcement and is capable of accommodating highway vehicles operating at speeds ranging from 16 km/h to 130 km/h. Type III WIM typically uses Single Load Cell (SLC) technology and is the most accurate WIM technology.
- Type IV WIM systems are not yet approved for use in North America but are intended to be used at weigh stations for enforcement purposes. These WIM systems are capable of detecting weights at speeds ranging from 3 km/h to 16 km/h and would have the potential to be the most accurate WIM technology as per the ASTM accuracy requirements.

WIM technology may be utilized for several other purposes, including pavement and bridge design, maintenance and rehabilitation initiatives, as well as for the development of compliance regulations, traffic operations, control guidelines, geometric design standards, and economic analysis for the development of equitable tax structures (Hajek et al. 1992, Schultz et al. 2005). Previous studies have demonstrated that the ability of WIM technology to generate commercial vehicle overloading patterns can significantly decrease the occurrence of overloading when incorporated into an enforcement regime (Stanczyk and Maeder 2002, Stephens et al. 2003, Serag et al. 2005, Conway and Walton 2005).

The Montana Department of Transportation (DOT) performed a two year study in 2000 to determine if WIM-directed weight enforcement could decrease the amount of damage inflicted by overweight commercial vehicles on Montana roadways (Stephens et al. 2003). Based on one year of data collection and WIM-directed enforcement, the study proved that WIM technology decreased the total number of overweight vehicles on the enforced roadways from 8.5 percent to 6.8 percent; thus facilitating a decrease in the overall amount carried by each overweight vehicle from 7,100 lb to 5,300 lb (Stephens et al. 2003). Therefore, incorporating overloading trends as observed through the use of WIM technology into existing enforcement programs correlated to a decrease in the roadway damage inflicted by overweight commercial vehicles.

Increasing domestic and international trade has caused great growth in the North American freight industry. Consequently, existing roadways, weigh stations and enforcement efforts are being pushed to exceed their original design capacity, resulting in accelerated infrastructure deterioration, as well as weigh station congestion and avoidance (Hallenbeck et al. 2002, Cunagin et al. 1997, Andrle et al. 2002). In addressing the issue of commercial vehicle mobility, the U.S. created a federal program called CVISN (Commercial Vehicle Information Systems and Networks) that works with ITS (including WIM) and communications technologies to increase the efficiency of freight mobility and regulatory efforts (Hallenbeck et al. 2002). The corresponding Canadian counterpart of CVISN is called Advantage I-75/AVION and is located in the province of Ontario (Hallenbeck et al. 2002). The concept of the CVISN program allows for mainline mobile credential, permit and weight checks, thereby reducing the requirement for trucks to stop.

The Province of Manitoba, in conjunction with the University of Manitoba Transport Information Group (UMTIG), is also participating in an on-going study assessing the application of WIM technology to a developing provincial traffic information system called the Manitoba Highways Truck Traffic Information System (MHTTIS) (Clayton et al. 2002, Zhi et al. 1999). MHTTIS relies on various data sources such as static weigh stations, WIM, and Automated Vehicle Classifiers (AVC), to provide input into highway planning, traffic engineering and design initiatives (Clayton et al. 2002). The study has shown that WIM/AVC devices have a great potential for developing an understanding of truck traffic within a particular region by identifying trends in freight movement (Clayton et al. 2002).

Due to the current lack of CVO monitoring within urban jurisdictions, new methods are required to collect CVO data on major urban corridors. The implementation of WIM and video technology on urban corridors facilitates the detection of gross vehicle weight (GVW) and axle loads of a vehicle, as well as the identification of vehicle class, speed and traffic density (Conway and Walton 2005, Andrle et al. 2002). The data obtained from this system allows for monitoring of the pavement design life and maintenance requirements through the survey of repeated heavy vehicle loadings (World Road Association 2004).

Previous studies have been completed which focus on the application of virtual weigh stations consisting of WIM and video systems operating together on main lanes of heavily-traveled rural corridors. A study performed in Kentucky identified methods through which virtual WIM technology could be employed for monitoring, and a similar study in Indiana identified an increase in the efficiency of overweight vehicle identification for weighing through the use of virtual WIM for screening (Conway and Walton 2005, Rodier et al. 2006). However, little effort has been put towards the utilization of WIM technology to quantitatively analyze urban CVO load spectra, frequency and the deleterious effects on urban roadway networks.

The AASHTO flexible pavement design equation is based on the assumption that road behaviour performance indicators such as deformation and cracking are a linear relationship (Berthelot et al. 2005). However, the varying pavements structures combined with dramatic increases in truck weights and dimensions facilitate non-linear road performance indicator relationships (Berthelot et al. 2005). As such, actual loadings and subsequent pavement performance may deviate considerably from the AASHTO flexible pavement roadway design (Berthelot et al. 2005). In order to realistically model the inelastic and non-linear behaviour of urban pavements, knowledge of vehicle weights, configurations, dynamics and tire characteristics, as well as environmental conditions and pavement material behaviours is imperative (Berthelot et al. 2005). As such, Berthelot et al (2005) proposed that the dynamic load profile representing actual field state traffic loads measured by WIM could be utilized to specify more realistic laboratory-field relationships.

## 2.4 Case Study Background: The City of Saskatoon

The City of Saskatoon has taken on the role of the industrial hub of Saskatchewan, resulting in major increases in commercial traffic within its main city corridors (Berthelot et al. 2005). As a result, many of the main roadways within the City's limits are exhibiting signs of severe structural distress in the form of localized fatigue cracking and extensive rutting, as shown in Figures 2.3 and 2.4.

**Figure 2.3- Severe Fatigue Cracking on Circle Drive, Saskatoon (C. Berthelot 2005)**

**Figure 2.4- Rutting and Reflective Cracking, Circle Drive, Saskatoon (C. Berthelot 2005)**

Commercial traffic in the province of Saskatchewan has increased appreciably due to the abandonment of rail lines, industry growth and increased trade with the United States (SDHT 2005). As a result, the provincial government is planning several projects aimed at accommodating the increased commercial vehicle demand on rural highways (SDHT 2005). However, the movement towards increased truck dimensions and volumes on rural roadways facilitates an accelerated depreciation of the urban roadway network in the City of Saskatoon. Urban pavements have thinner structures and are exposed to adverse driving conditions where speeds are reduced, stop and go conditions are increased, turning and shear stresses are amplified and traffic is progressively channelized. This creates an environment where roadway damages may be greater than those predicted by the AASHTO fourth power relationship (Taylor et al. 2000).

# CHAPTER 3 - RELIABILITY ANALYSIS OF CIRCLE DRIVE VWIM SYSTEM

The Circle/Preston VWIM system was calibrated according to ASTM standards prior to data collection. Reliability of the calibrated system was validated using repeated trials of truck configurations that commonly operate within the City of Saskatoon.

## 3.1 Saskatoon VWIM System and Site Description

The Circle/Preston VWIM system, illustrated in Figure 3.1, was installed in 2005 on Circle Drive and consists of the following components:

- ASTM Type I bending plate WIM installed in all lanes (two northbound and two southbound) for a total of eight bending plates;
- Loop arrays prior to and after the bending plates in every lane for a total of eight loop sensors, and;
- An image-capture system including a side-imaging (side-fire) camera adjacent to the curb lanes on the north and south sides of the road and two license plate cameras over the curb lanes in either direction of travel.

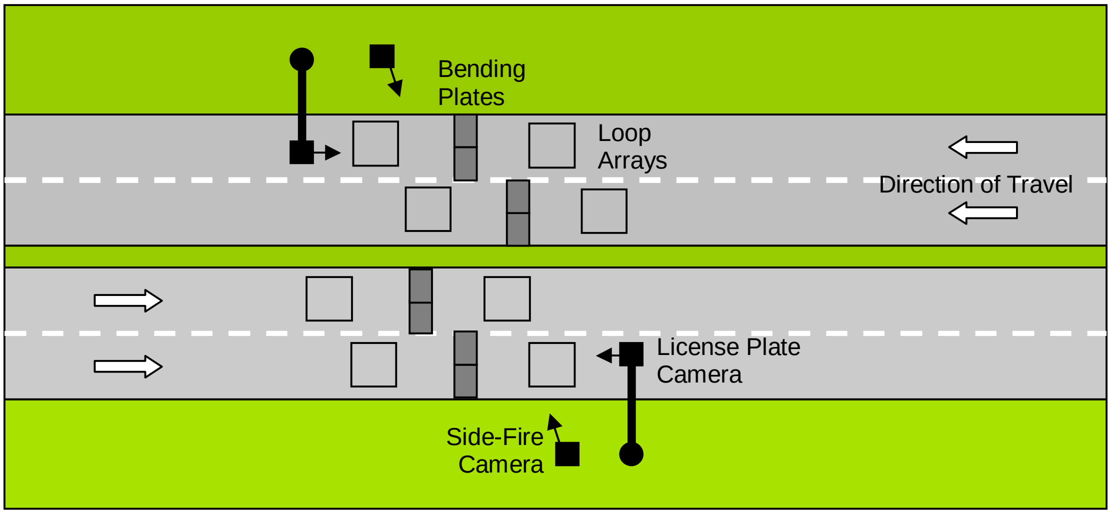

**Figure 3.1 - Schematic of Circle/Preston VWIM Site Layout**

Circle Drive was selected for the VWIM system evaluation because it is a main corridor through the City of Saskatoon. Circle Drive acts as a primary truck route and freeway for inter and intra-urban traffic, as well as for inter-provincial and international traffic. Side-fire cameras were installed beside the curb lanes on either side of the roadway and are triggered by vehicles passing over detection loops in both the curb and median lanes. License plate cameras were installed over the curb lanes in each direction of travel and are also triggered by vehicles passing over the detection loops. Only the curb lanes were given license plate video coverage based on the assumption that the majority of truck traffic would travel in the curb lanes. Images are recorded by the imaging system and linked with their corresponding WIM vehicle record through the system electronics. The WIM bending plate system records the gross vehicle and individual axle weights, vehicle length, speed and classification for all vehicles in all lanes.

The International Roughness Index (IRI) was measured at this site in October 2005. ASTM 1318-02 suggests that the roadway surface is smooth in advance of the WIM scales for 60 m and for 30 m beyond the WIM scales to facilitate reliable WIM performance. The IRI results for Circle Drive at the VWIM site were 1.5 mm/m in the eastbound direction of travel and 1.3

mm/m for the westbound direction of travel. New pavements are typically expected to have IRI results ranging from 1.5 mm/m to 3.5 mm/m. This indicated that the pavement at the Circle Drive VWIM site was relatively smooth and in good operating condition for the purpose of reliable WIM performance.

## 3.2 Calibration of VWIM System

The VWIM system was calibrated according to ASTM 1318-02 Type I specifications by International Road Dynamics (IRD) Inc. on May 11, 2006. ASTM 1318-02 specifies that the 95 percent tolerance for a Type I WIM system is ±20 percent for axle loads, ±15 percent for axle group loads and ±10 percent for GVW. The VWIM system was calibrated using a 6-axle tractor semi-trailer with the following static weights:

**Table 3.1 - Calibration Vehicle Axle Group Weights**

| Steering Axle | Drive Axle | Trailer Axles | GVW |
|---|---|---|---|
| 4,930 kg | 16,225 kg | 19,955 kg | 41,110 kg |

Upon completion of the preliminary calibration, ten repeat passes of the calibration truck were completed on each lane to obtain the final calibration results. A summary of the calibration results are provided in Table 3.2 and Figure 3.2. The coefficient of variance (CV) of the WIM-measured weights from the ten trial runs across all lanes were relatively uniform and ranged from 4 percent to 5 percent for the steering axle group, 2 percent to 4 percent for the drive axle group, 4 percent to 6 percent for the trailer axle group and 2 percent to 4 percent for the overall GVW of the calibration truck.

**Table 3.2 - Summary of Calibration Trials**

| Axle Group | Calibration Measure | WB Curb Lane | WB Median Lane | EB Curb Lane | EB Median Lane |
|---|---|---|---|---|---|
| Steering Axle Group | Mean Measured (kg) | 5,085 | 4,930 | 5,318 | 4,950 |
| | St. Dev. Measured | 217 | 197 | 291 | 270 |
| | Coefficient of Variance (percent) | 4.3 | 4.0 | 5.5 | 5.5 |
| | Mean Difference (kg) | 155 | 0 | 388 | 20 |
| Drive Axle Group | Mean Measured (kg) | 16,251 | 15,921 | 16,028 | 16,044 |
| | St. Dev. Measured | 467 | 366 | 638 | 319 |
| | Coefficient of Variance (percent) | 2.9 | 2.3 | 4.0 | 2.0 |
| | Mean Difference (kg) | 26 | -304 | -197 | -181 |
| Trailer Axle Group | Mean Measured (kg) | 18,980 | 20,121 | 19,197 | 20,503 |
| | St. Dev. Measured | 1,207 | 853 | 1,218 | 933 |
| | Coefficient of Variance (percent) | 6.4 | 4.2 | 6.3 | 4.6 |
| | Mean Difference (kg) | -975 | 166 | -758 | 548 |
| GVW | Mean Measured (kg) | 40,316 | 40,972 | 40,543 | 41,498 |
| | St. Dev. Measured | 1,489 | 1,141 | 1,742 | 936 |
| | Coefficient of Variance (percent) | 3.7 | 2.8 | 4.3 | 2.3 |
| | Mean Difference (kg) | -794 | -138 | -567 | 388 |

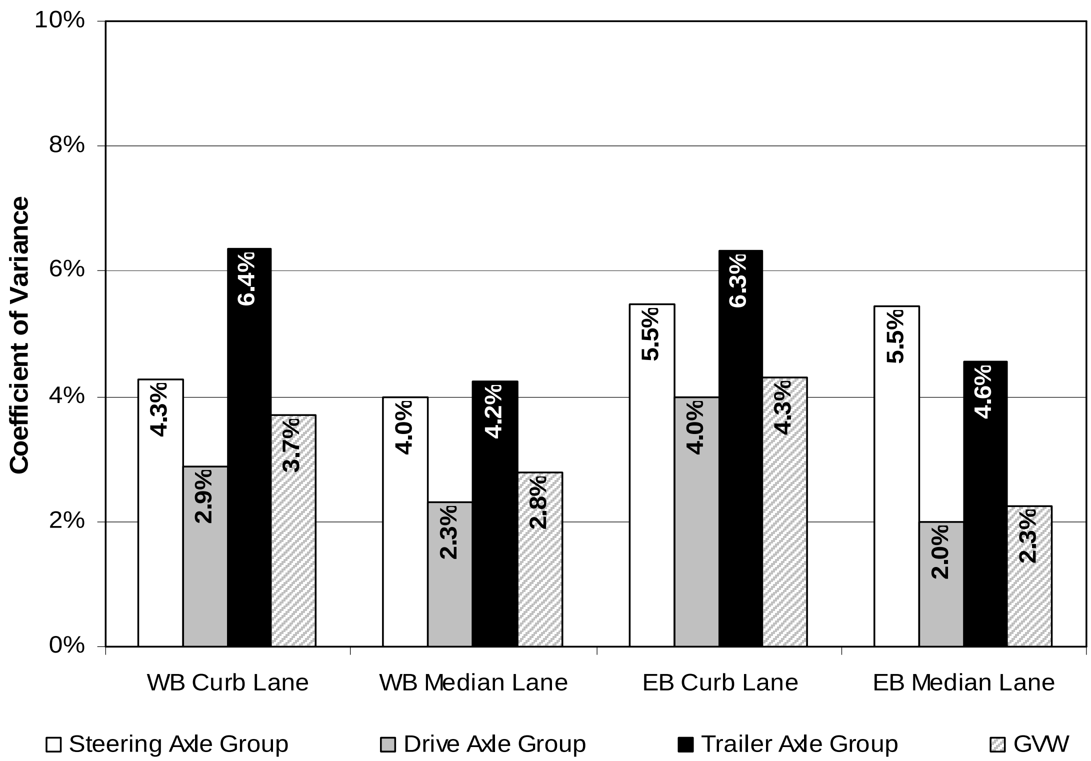


**Figure 3.2 – Coefficient of Variance of Repeat Calibration Trial Runs**

Figure 3.3 illustrates the VWIM system GVW calibration results grouped by speed and lane. The percent difference between the WIM GVW and the static GVW was calculated using Equation 3.1.

$$Percent \quad Difference = \frac{Weight_{WIM} - Weight_{Static}}{Weight_{Static}} \qquad [3.1]$$

Calibration results by lane are summarized in Figure 3.3 and complete results are located in Appendix A. As seen in Figure 3.3, the largest deviations between WIM GVW and static GVW were observed within the 60 km/h speed bin (ranging from 60 km/h to 69 km/h) in all lanes. The mean percent difference between the WIM and static GVW in the westbound curb lane increased from -2.3 percent in the 50 km/h speed bin to -9.0 percent in the 60 km/h speed bin. The negative differences meant that the westbound curb lane WIM was producing vehicle weights that were smaller than the static vehicle weight. The westbound median lane percent difference shifted from positive to negative between the 50 km/h speed bin and the 60 km/h speed bin. This shift indicated that the westbound median lane WIM went from producing weights that were heavier than the static weight to producing weights that were lighter than the static weight. The calibration results for the eastbound curb and median lanes also shifted between these speed bins in that the curb lane went from producing lighter than static weights to producing heavier than static weights, and the median lane shifted in the opposite direction.

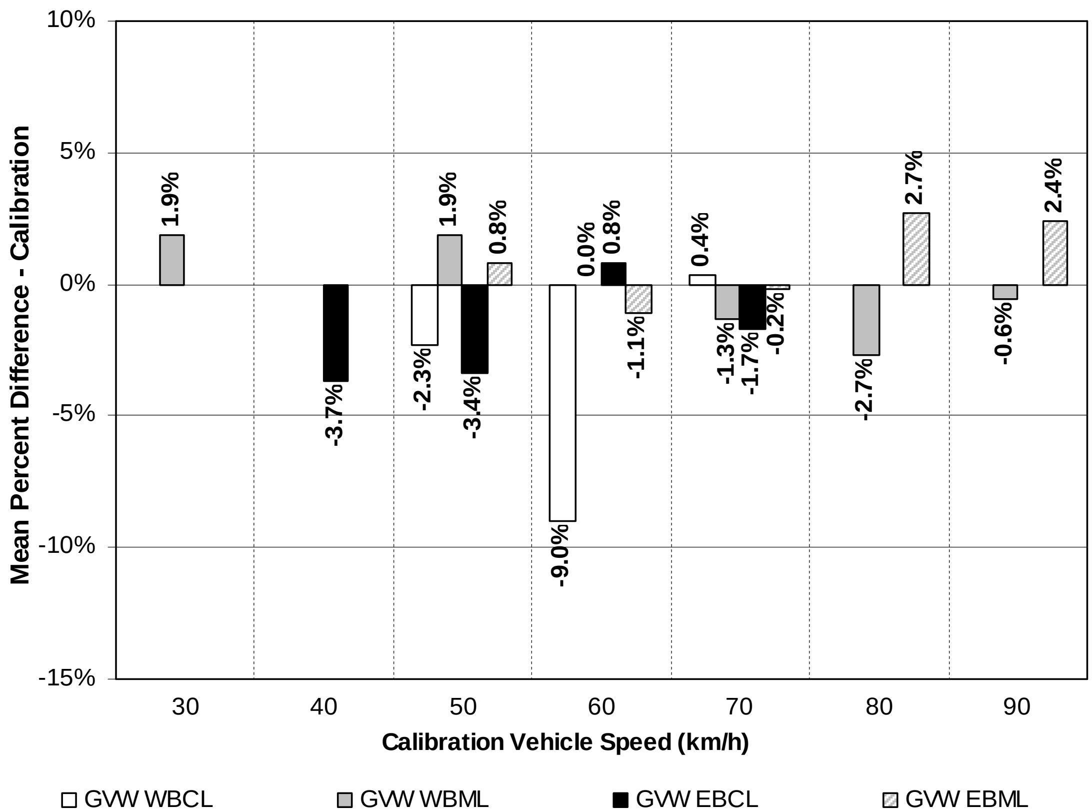


**Figure 3.3 - Mean Calibration Results with Respect to Travel Speed across All Lanes**

Based on the calibration results, the eastbound curb lane had the largest percent difference between the average WIM weights and static weights were, and the westbound curb lane had the largest percent difference for the trailer axle groups. The largest standard deviations for all axle group weights occurred in the eastbound curb lane. This would typically be indicative of increased truck dynamics over the scales due to rougher pavement surface or weaker pavement structure prior to the WIM scales. However, 2005 IRI testing results showed a difference of only 0.2 mm/m between the westbound and eastbound directions. Additionally, truck and load were kept constant throughout the calibration. Consequently, the variation between eastbound and westbound measured weight standard deviations was most likely due to variability within the WIM scales caused either during installation or from wear.

WIM final calibration factors were obtained by calculating the mean percent difference of the average WIM-measured weights from the 10 calibration vehicle trials versus the static axle weights and GVW of the calibration vehicle, as illustrated in Equation 3.2.

$$Final \quad Calibration \quad Factor = \frac{\sum_i^n \frac{(Weight_{WIM\,(i)} - Weight_{STATIC})}{Weight_{STATIC}}}{n} \qquad [3.2]$$

As seen in Figure 3.4, the eastbound curb lane had the largest calibration factor for the steering axle group at 7.87 percent. The westbound curb lane had the largest calibration factor for the trailer axle groups at -4.88 percent.

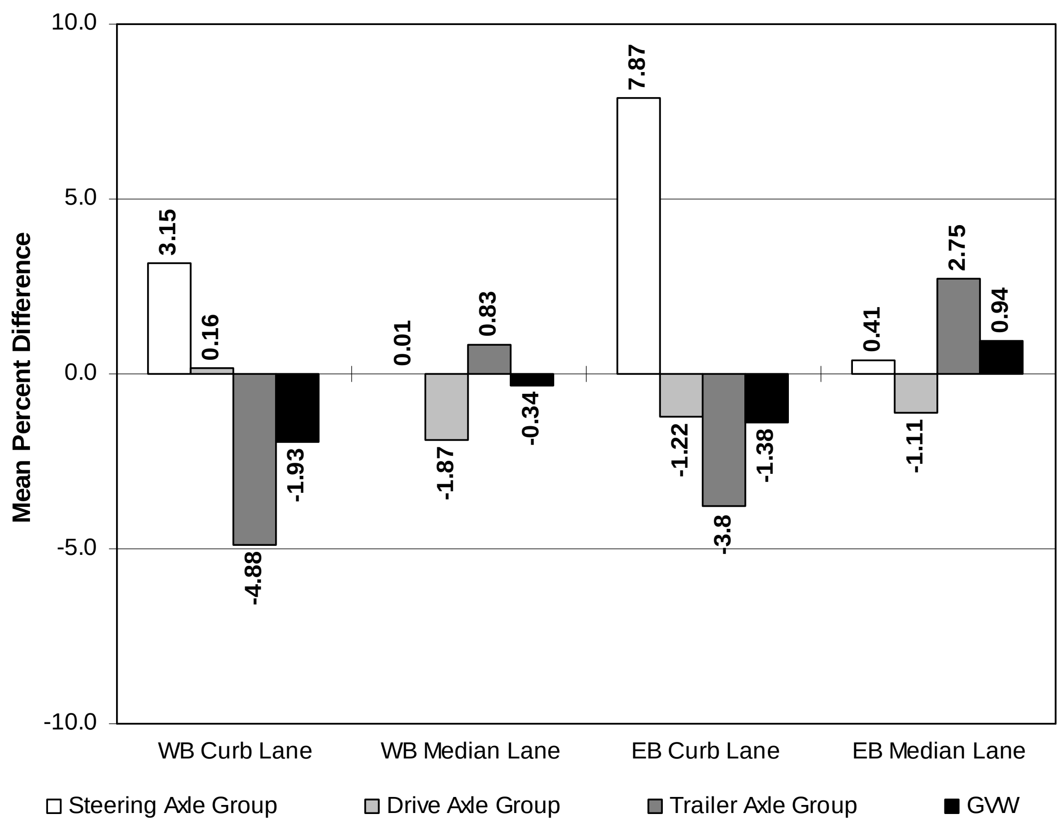


**Figure 3.4 - Final Calibration Factors per Lane per Axle Group**

### 3.3 VWIM System Reliability Validation

Reliability of the VWIM system was validated after calibration during the week of May 25th, 2006. Test truck configurations representative of typical vehicles operating on Circle Drive in Saskatoon (Bushman and Berthelot 2003) were utilized for the system validation, including:

- Two and three axle straight trucks;
- Five and six axle semi-trailer units, and;
- Eight axle semi-trailer combination units.

The reliability analysis was completed using 15 repeated trials of each of the aforementioned truck configurations with known static weight operating at speeds ranging from 60 km/h to 80 km/h. This speed range was representative of the lowest speed bin in the WIM system classification algorithm and the typical operating speeds of commercial vehicles on this section of Circle Drive. The identity of the test truck within the traffic stream was confirmed using the video capture technology at the Circle/Preston VWIM system, as illustrated in Figure 3.5.

**Figure 3.5 - License Plate and Side-Fire Image Vehicle Verification of Validation Truck**

The video system was used to obtain images of the license plate and side of the test truck. License plate cameras were only configured for the curb lanes in both directions. The side imaging cameras, though capable of capturing images in both the median and curb lanes, were configured primarily for the curb lanes. As such, there was potential for vehicular occlusion of traffic in the median lane if a vehicle were present in the curb lane. Consequently, the reliability of the WIM scales was only validated for the curb lanes and the assumption was made that the median lanes would exhibit similar trends to those observed in the corresponding curb lane.

Based on the final calibration results, the mean percent difference between the WIM and static GVW was -1.38 percent in the eastbound curb lane and -1.93 percent in the westbound curb lane, with overall CV results of 4.30 and 3.69. This indicated that the WIM scales in both curb lanes were generating GVW measurements that were lighter than the static GVW.

Axle weight and GVW measurements from each trial run were recorded and adjusted to compensate for the remaining final calibration error to validate the reliability of the WIM system. The sample mean, range, standard deviation and coefficient of variance were assessed to determine uniformity within GVW and axle group weight measurements. The same truck type, driver and commodity (sand and gravel), were used for the five and six axle tractor semi-trailers, and the eight axle combination unit measurements. The five, six and eight axle units, including driver, were donated in kind from Pavement Scientific International Inc. The driver and load commodity (soil and gravel) were donated by the City of Saskatoon for the portion of validation utilizing two and three axle straight trucks.

Reliability validation results were adjusted for the final calibration error and are summarized by truck configuration for the westbound and eastbound curb lanes in Tables 3.3 and 3.4. Full data tables for each trial are located in Appendix B. As seen in Tables 3.3 and 3.4, the reliability validation results for all vehicle configurations in both directions of travel confirmed that the errors within the WIM records were within acceptable ranges specified in ASTM 1318-02 Type I standards (±15 percent for axle group and ±10 percent for GVW) (ASTM International E 1318-02).

**Table 3.3 –Reliability Assessment Results: All Configurations in Westbound Curb Lane**

| | Steering Axle | Drive Axle | Trailer Tridem Axle | Trailer Tandem Axle | GVW |
|---|---|---|---|---|---|
| **TWO AXLE STRAIGHT TRUCK** | | | | | |
| Static Wt (kg) | 4,600 | 6,110 | - | - | 10,710 |
| Mean Wt (kg) | 4,742 | 6,169 | - | - | 10,911 |
| St. Dev. | 103 | 183 | - | - | 205 |
| CV (%) | 2.2 | 3.0 | - | - | 1.9 |
| Mean Diff (%) | -3.1 | -1.0 | - | - | -1.9 |
| **THREE AXLE STRAIGHT TRUCK** | | | | | |
| Static Wt (kg) | 5,200 | 49,665 | - | - | 21,865 |
| Mean Wt (kg) | 5,701 | 18,179 | - | - | 23,871 |
| St. Dev. | 140 | 398 | - | - | 450 |
| CV (%) | 2.5 | 2.2 | - | - | 1.9 |
| Mean Diff (%) | -9.6 | -9.1 | - | - | -9.2 |
| **FIVE AXLE SEMI-TRAILER COMBINATION UNIT** | | | | | |
| Static Wt (kg) | 5,025 | 13,760 | - | 14,705 | 33,490 |
| Mean Wt (kg) | 5,162 | 13,149 | - | 15,340 | 33,651 |
| St. Dev. | 103 | 194 | - | 290 | 465 |
| CV (%) | 2.0 | 1.5 | - | 1.9 | 1.4 |
| Mean Diff (%) | -2.7 | 4.4 | - | -4.3 | -0.5 |
| **SIX AXLE SEMI-TRAILER COMBINATION UNIT** | | | | | |
| Static Wt (kg) | 4,755 | 17,860 | 13,195 | - | 35,810 |
| Mean Wt (kg) | 4,692 | 17,901 | 14,095 | - | 36,689 |
| St. Dev. | 103 | 281 | 388 | - | 552 |
| CV (%) | 2.2 | 1.6 | 2.8 | - | 1.5 |
| Mean Diff (%) | 1.3 | -0.2 | -6.8 | - | -2.5 |
| **EIGHT AXLE SEMI-TRAILER COMBINATION UNIT** | | | | | |
| Static Wt (kg) | 4,890 | 17,410 | 22,940 | 14,825 | 60,065 |
| Mean Wt (kg) | 4,646 | 17,285 | 22,951 | 15,120 | 60,002 |
| St. Dev. | 129 | 279 | 568 | 335 | 983 |
| CV (%) | 2.8 | 1.6 | 2.5 | 2.2 | 1.6 |
| Mean Diff (%) | 5.0 | 0.7 | 0.0 | -2.0 | 0.1 |

**Table 3.4 –Reliability Assessment Results: All Configurations in Eastbound Curb Lane**

| | Steering Axle | Drive Axle | Trailer Tridem Axle | Trailer Tandem Axle | GVW |
|---|---|---|---|---|---|
| **TWO AXLE STRAIGHT TRUCK** | | | | | |
| Static Wt (kg) | 4,600 | 6,110 | - | - | 10,710 |
| Mean Wt (kg) | 4,778 | 6,932 | - | - | 11,709 |
| St. Dev. | 801 | 745 | - | - | 1,521 |
| CV (%) | 16.8 | 10.8 | - | - | 13.0 |
| Mean Diff (%) | -3.9 | -13.4 | - | - | -9.3 |
| **THREE AXLE STRAIGHT TRUCK** | | | | | |
| Static Wt (kg) | 5,200 | 49,665 | - | - | 21,865 |
| Mean Wt (kg) | 5,948 | 15,631 | - | - | 21,579 |
| St. Dev. | 1,228 | 1,025 | - | - | 1,739 |
| CV (%) | 20.6 | 6.6 | - | - | 8.1 |
| Mean Diff (%) | -14.4 | 6.2 | - | - | 1.3 |
| **FIVE AXLE SEMI-TRAILER COMBINATION UNIT** | | | | | |
| Static Wt (kg) | 5,025 | 13,760 | - | 14,705 | 33,490 |
| Mean Wt (kg) | 5,546 | 14,121 | - | 15,933 | 35,599 |
| St. Dev. | 471 | 1,055 | - | 2,047 | 3,467 |
| CV (%) | 8.5 | 7.5 | - | 12.8 | 9.7 |
| Mean Diff (%) | -10.4 | -2.6 | - | -8.3 | -6.3 |
| **SIX AXLE SEMI-TRAILER COMBINATION UNIT** | | | | | |
| Static Wt (kg) | 4,755 | 17,860 | 13,195 | - | 35,810 |
| Mean Wt (kg) | 5,450 | 18,704 | 15,130 | - | 39,284 |
| St. Dev. | 378 | 888 | 1,204 | - | 1,985 |
| CV (%) | 6.9 | 4.7 | 8.0 | - | 5.1 |
| Mean Diff (%) | -14.6 | -4.7 | -14.7 | - | -9.7 |
| **EIGHT AXLE SEMI-TRAILER COMBINATION UNIT** | | | | | |
| Static Wt (kg) | 4,890 | 17,410 | 22,940 | 14,825 | 60,065 |
| Mean Wt (kg) | 5,378 | 18,016 | 24,434 | 15,844 | 63,673 |
| St. Dev. | 140 | 606 | 979 | 740 | 2,002 |
| CV (%) | 2.6 | 3.4 | 4.0 | 4.7 | 3.1 |
| Mean Diff (%) | -10.0 | -3.5 | -6.5 | -6.9 | -6.0 |

As seen in Figure 3.6, the reliability validation for the westbound curb lane WIM indicated that the largest mean difference between the steering axle group WIM and static weights occurred from the two and three axle straight truck configurations, and the eight axle semi-trailer configuration. The five axle semi-trailer WIM measurements had the largest mean difference from static weight for the drive axle group. The six axle semi-trailer WIM measurements produced the greatest difference from the static trailer tridem axle group weights.

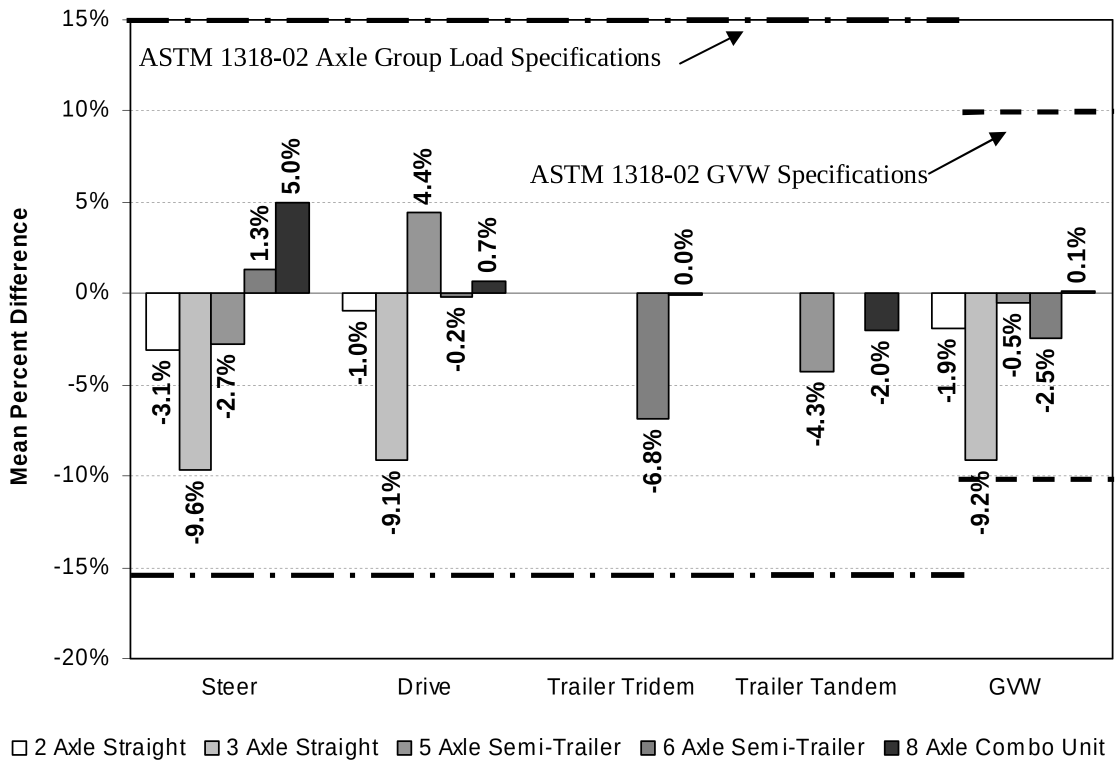


**Figure 3.6 - Westbound Mean Percent Difference across all Configurations**

As seen in Figure 3.7, the reliability validation of the eastbound curb lane WIM system displayed similar trends to the westbound curb lane where the largest percent difference between the WIM and static weights were produced by the steer axle groups of the three, five and eight axle configurations. The two axle straight truck produced larger mean differences between the WIM and static weight of the drive axle group. The six axle semi-trailer unit generated the greatest mean difference between WIM and static weight of the trailer tridem axle group. The reliability validation for the five truck configurations confirmed that the WIM weights taken in the eastbound curb lane were exhibiting higher variability as compared to the westbound curb lane, as noted in the initial system calibration.

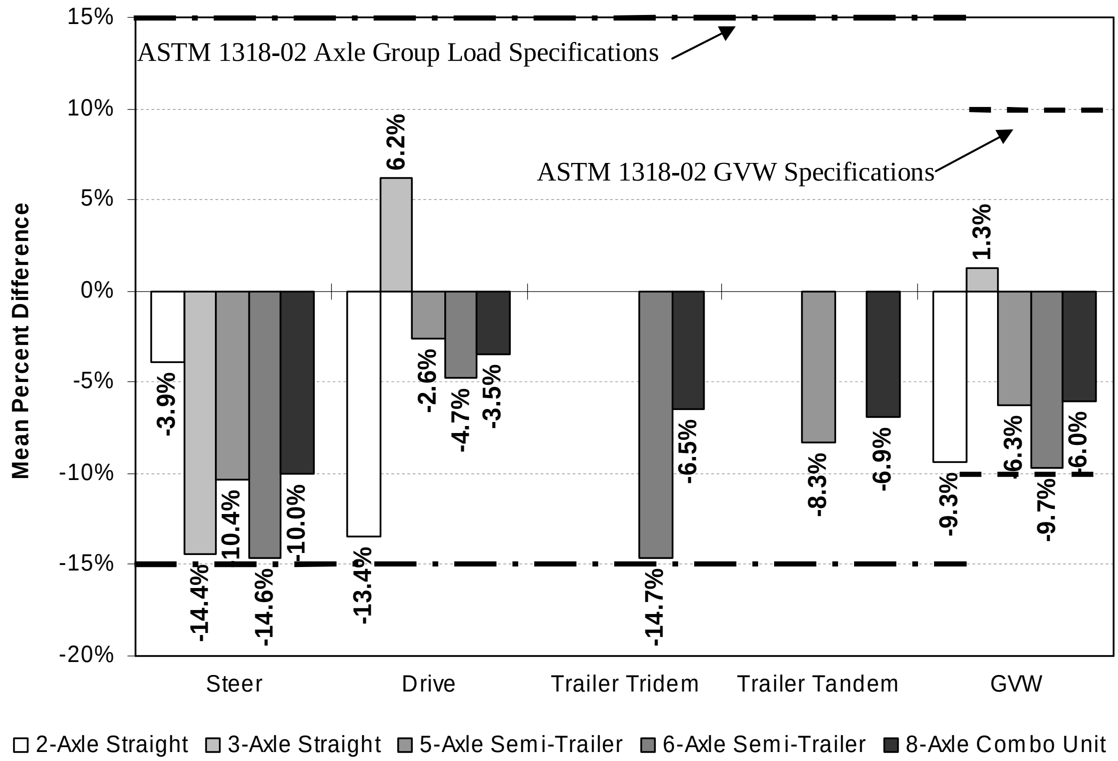


**Figure 3.7 - Eastbound Mean Percent Difference across all Configurations**

As presented in Table 3.3, the coefficient of variance of the westbound curb lane WIM axle and GVW measurements were fairly uniform across the test vehicle configurations and ranged from 1.4 percent to 3.0 percent. The small range between the coefficients of variance indicated that vehicle configuration and travel speed did not adversely affect the reliability of the WIM measurements in this lane.

The eastbound curb lane coefficient of variance for WIM axle and GVW measurements were quite large, as summarized in Table 3.4. The coefficient of variance for the steering axle group ranged from 2.6 percent for the eight axle configuration to 20.6 percent for the three axle configuration. The eastbound steering axle coefficients of variation were higher for the two and three axle straight trucks than for the larger five, six and eight axle truck configurations. It was noted that the eastbound coefficients of variance typically decreased with increasing truck weight and size, indicating that added weight and/or the addition of a B-train had a potential stabilizing effect on the eastbound WIM reliability.

### 3.5 Time Dependent Shift in VWIM System Error

The WIM error remaining after calibration, summarized in Table 3.5, indicated that both the eastbound and westbound curb lane WIM were weighing lighter than the static vehicle weight. The error obtained from the reliability validation conducted two weeks after calibration indicated that both curb lanes were weighing heavier than actual vehicle weights.

A total shift in error of 4.4 percent and 11.1 percent for the westbound and eastbound curb lanes was observed two weeks after the initial calibration, as presented in Table 3.5 and Figure 3.8. As such, it was concluded that the WIM error had shifted over time. This also indicated that the vehicle spectra data obtained after the initial calibration may need to be adjusted to reflect the shift in WIM system error prior to further analysis.

**Table 3.5 - Shift in GVW Error of WIM System**

| Lane | GVW ERROR IN WIM MEASUREMENTS | | Total Shift in Error |
|---|---|---|---|
| | Post-Calibration | Reliability Validation | |
| WB Curb Lane | 0.0193 | -0.0245 | 0.0438 |
| EB Curb Lane | 0.0138 | -0.0970 | 0.1108 |

Based on standard industry practices, WIM system error is generally calibrated under the assumption that they are a linear function over a short period of time (Taylor 2008). Therefore, it was assumed that the shift in WIM error was a linear function, as illustrated in Figure 3.8.

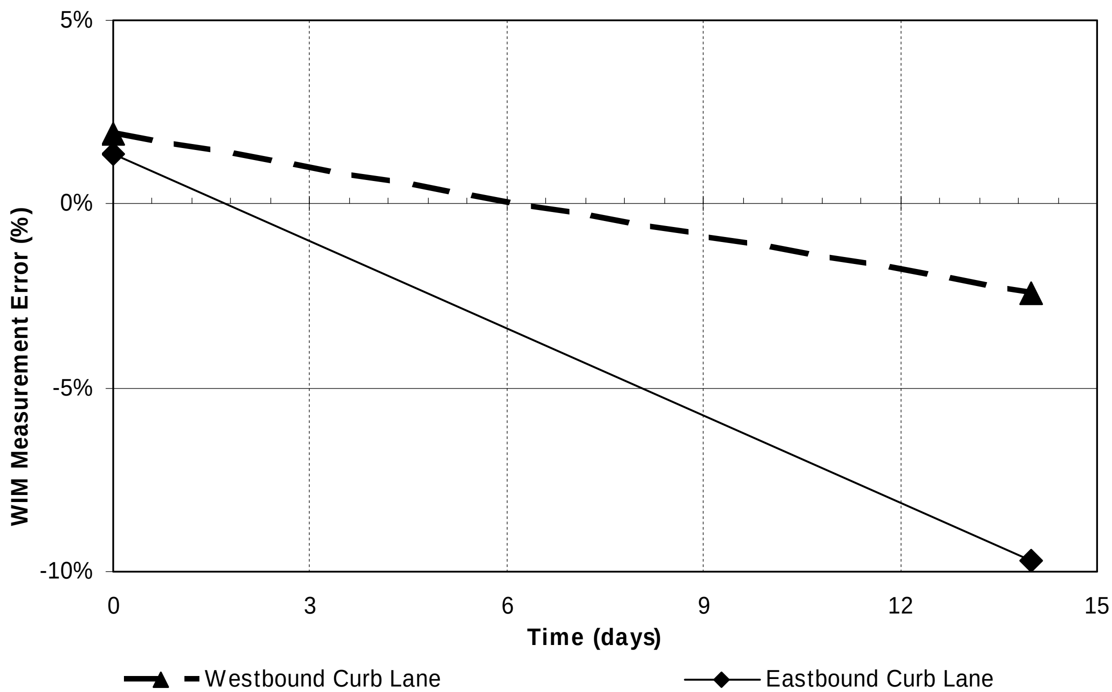


**Figure 3.8 - Shift in GVW Error of WIM Measurements**

The vehicle weight spectra obtained from the VWIM system was adjusted in recognition of the effects of the error shift on larger vehicle weight records. Daily error factors were created assuming that the error trends for each of the major truck configurations would follow those observed for the six axle semi-trailer unit used in both the calibration and system validation. Data for comparison was only available for curb lanes and it was assumed that the daily shift in error for median lanes would be similar to that calculated for the corresponding curb lane. Since vehicles representative of straight trucks with tandem steering and four axle tractor-semi units were not available during the system validation, it was assumed that these truck types would exhibit the same error shift as the similarly-configured three axle straight truck and five axle tractor-semi units.

The daily shift in WIM system error was calculated as a percentage of the final error obtained for the six axle tractor-semi configuration in the validation assessment. The resulting daily shift factor was applied to the daily average GVW and axle group weights for each major truck configuration within each lane. The corrected weights were back-calculated from the day of system validation, May 24th to 26th, 2006, to the date of initial calibration, May 11th, 2006. The following assumptions were made to complete the calculation:

- Each of the major truck configurations would exhibit daily percent shifts in WIM error similar to those calculated for the six axle semi-trailer unit in both GVW and axle group weights;
- The straight trucks with tandem steering would demonstrate the same shifts in error as observed for the three axle straight trucks;
- The four axle tractor-semi units would demonstrate the same shifts in error as observed for the five axle tractor-semi configurations, and;
- The daily shifts in error would be similar between the trailer tridem axle groups and trailer tandem axle groups.

Daily error factors were applied to the GVW and axle group weights for the data set presented in Chapter 4 and are summarized in Tables 3.6 and 3.7. Full data tables are located in Appendix C. As seen in Table 3.6, all of the daily error factors were less than ±one percent with the exception of two truck configurations in the westbound curb lane.

**Table 3.6 – GVW Error Daily Linear Shift Factors by Vehicle Class**

| Vehicle Class | EBCL | EBML | WBML | WBCL |
|---|---|---|---|---|
| 2 Axle Straight | - 0.00651 | - 0.00651 | 0.00034 | 0.00034 |
| 3 Axle Straight | 0.00265 | 0.00265 | - 0.02443 | - 0.02443 |
| Straight w/ Tandem Steering | 0.00265 | 0.00265 | - 0.02443 | - 0.02443 |
| 4 Axle Tractor-Semi | - 0.00405 | - 0.00405 | 0.00485 | 0.00485 |
| 5 Axle Tractor-Semi | - 0.00405 | - 0.00405 | 0.00485 | 0.00485 |
| 6 Axle Tractor-Semi | - 0.00685 | - 0.00685 | - 0.00174 | - 0.00174 |
| 8 Axle Tractor-Semi Combo | - 0.00384 | - 0.00384 | 0.00683 | 0.00683 |

**Table 3.7 –Axle Group Weight Daily Linear Error Shift Factors by Vehicle Class**

| | Steering Axle | Drive Axle Group | Trailer Tridem Axle Group | Trailer Tandem Axle Group |
|---|---|---|---|---|
| **TWO AXLE STRAIGHT TRUCK** | | | | |
| EBCL | - 0.00068 | - 0.01164 | - | - |
| EBML | - 0.00068 | - 0.01164 | - | - |
| WBML | - 0.00156 | 0.00078 | - | - |
| WBCL | - 0.00156 | 0.00078 | - | - |
| **THREE AXLE STRAIGHT TRUCK** | | | | |
| EBCL | - 0.00347 | 0.00781 | - | - |
| EBML | - 0.00347 | 0.00781 | - | - |
| WBML | - 0.01073 | - 0.00549 | - | - |
| WBCL | - 0.01073 | - 0.00549 | - | - |
| **STRAIGHT TRUCK WITH TANDEM STEERING** | | | | |
| EBCL | - 0.00347 | 0.00781 | - | - |
| EBML | - 0.00347 | 0.00781 | - | - |
| WBML | - 0.01073 | - 0.00549 | - | - |
| WBCL | - 0.01073 | - 0.00549 | - | - |
| **FOUR AXLE SEMI-TRAILER COMBINATION UNIT** | | | | |
| EBCL | - 0.00251 | - 0.00120 | - | - 0.00633 |
| EBML | - 0.00251 | - 0.00120 | - | - 0.00633 |
| WBML | - 0.00111 | 0.00489 | - | - 0.00337 |
| WBCL | - 0.00111 | 0.00489 | - | - 0.00337 |
| **FIVE AXLE SEMI-TRAILER COMBINATION UNIT** | | | | |
| EBCL | - 0.00251 | - 0.00120 | - | - 0.00633 |
| EBML | - 0.00251 | - 0.00120 | - | - 0.00633 |
| WBML | - 0.00111 | 0.00489 | - | - 0.00337 |
| WBCL | - 0.00111 | 0.00489 | - | - 0.00337 |
| **SIX AXLE SEMI-TRAILER COMBINATION UNIT** | | | | |
| EBCL | - 0.00371 | - 0.00294 | - 0.01207 | - |
| EBML | - 0.00371 | - 0.00294 | - 0.01207 | - |
| WBML | 0.00453 | 0.00131 | - 0.00691 | - |
| WBCL | 0.00453 | 0.00131 | - 0.00691 | - |
| **EIGHT AXLE SEMI-TRAILER COMBINATION UNIT** | | | | |
| EBCL | - 0.00241 | - 0.00205 | - 0.00470 | - 0.00498 |
| EBML | - 0.00241 | - 0.00205 | - 0.00470 | - 0.00498 |
| WBML | 0.00965 | 0.00204 | 0.00259 | - 0.00014 |
| WBCL | 0.00965 | 0.00204 | 0.00259 | - 0.00014 |

### 3.6 VWIM System Calibration and Validation Summary

The purpose of this chapter was to calibrate the VWIM system and to validate the reliability of the system. Reliability validation was completed using repeated trials of truck configurations identified by Bushman and Berthelot (2003) as typical for the City of Saskatoon.

The Circle/Preston VWIM system was calibrated by International Road Dynamics Inc. using a six axle semi-trailer truck on May 11, 2006. The final calibration error was calculated for the individual axle groups and GVW.

The reliability of the VWIM system was validated using repeated trials of the following five commercial vehicle configurations:

- Two and three axle straight trucks;
- Five and six axle semi-trailer trucks, and;
- Eight axle semi-trailer units.

License plate video images were used to confirm the identity of the validation trucks within the vehicle stream. However, since these cameras were only in the curb lanes, reliability validation of the WIM system was only completed for the curb lanes. It was assumed that the median lanes would exhibit similar trends to those observed in their corresponding curb lane.

The westbound curb lane reliability validation resulted in coefficients of variance that were fairly low and uniform across all truck configurations, ranging from 1.4 percent to 3.0 percent. This indicated that vehicle configurations and travel speeds did not have a major effect on the reliability of the WIM measurements in this direction of travel. In contrast, the eastbound curb lane reliability validation resulted in a wide range of coefficients of variance, varying from 2.6 percent for the eight axle truck steering axle group to 20.6 percent for the three axle truck steering axle group. It was noted that the eastbound coefficients of variance typically decreased with increasing truck size, indicating that the added weight and/or the addition of a B-train had a stabilizing effect on any potential vehicle vibrations or bouncing prior to the scales.

The reliability validation concluded that the error of the Circle/Preston VWIM system shifted during the two weeks between the calibration and validation analyses. The six axle semi-trailer error shifted from 1.93 percent upon calibration to -2.45 percent during validation in the westbound curb lane, and from 1.38 percent upon calibration to -9.7 percent during validation in the eastbound curb lane. As such, a daily error factor was calculated to correct the GVW and axle group weights obtained for the sample vehicles in the load spectra under the assumption that the WIM error shift was a linear event.

# CHAPTER 4 - COMMERCIAL VEHICLE LOAD SPECTRA IN SASKATOON

In order to assess the consequences of commercial vehicle loading on different urban road types in Saskatoon, commercial vehicle load spectra were generated from the Circle/Preston VWIM site. The load spectra were used as a base line by which to interpret commercial vehicle loading on other urban road types.

## 4.1 Vehicle Load Spectra

VWIM vehicle data was collected from May 12$^{th}$ to May 18$^{th}$, 2006 for a total of 168 consecutive hours of data collection. Truck configurations were interpreted using a classification scheme, outlined in Table 4.1, based on a system used by the Saskatchewan Department of Highways and Transportation. Class 4 vehicles weighing less than 6,000 kg were omitted from the analysis to eliminate the effects of private vehicles on the spectra analysis.

An average daily truck volume of 2,440 trucks per day (tpd) was observed across the four lanes of the Circle/Preston VWIM site and a total of 17,084 truck WIM records generated. As illustrated in Figure 4.1, the majority of the truck population consisted of Class 4, 5, 6, 11, 12, 13 and 19 vehicles, which included:

- Two and three axle straight trucks;
- Tandem steering straight trucks;
- Four, five and six axle tractor-semi units, and;
- Eight axle tractor-semi combination units.

**Table 4.1 – Saskatchewan Truck Classification System**

| Vehicle Class | Vehicle Description/Configuration | Corresponding FHWA Class |
|---|---|---|
| 4 | Straight Truck, 2 Axles | 5 |
| 5 | Straight Truck, 3 Axles | 6 |
| 6 | Straight Truck with Tandem Steering | 7 |
| 7 | Truck and tandem Pony Trailer | 11 |
| 8 | Truck and Tridem Pony Trailer | 12 |
| 9 | Truck and Full Trailer, 5 Axles | 11 |
| 10 | Truck and Full Trainer, 6 Axles | 12 |
| 11 | Tractor and Semi-Trailer, 4 Axles | 8 |
| 12 | Tractor and Semi-Trailer, 5 Axles | 9 |
| 13 | Tractor and Semi-Trailer, 6 Axles | 10 |
| 14 | A-C Train, 6 Axles | 12 |
| 15 | A-C Train, 7 Axles | 13 |
| 16 | A-C Train, 8 Axles | 13 |
| 17 | C Train with Approved Dolly, 8 Axles | 13 |
| 18 | B-Train, 7 Axles | 13 |
| 19 | B-Train, 8 Axles | 13 |
| 20 | B-Train, 9 Axles | - |

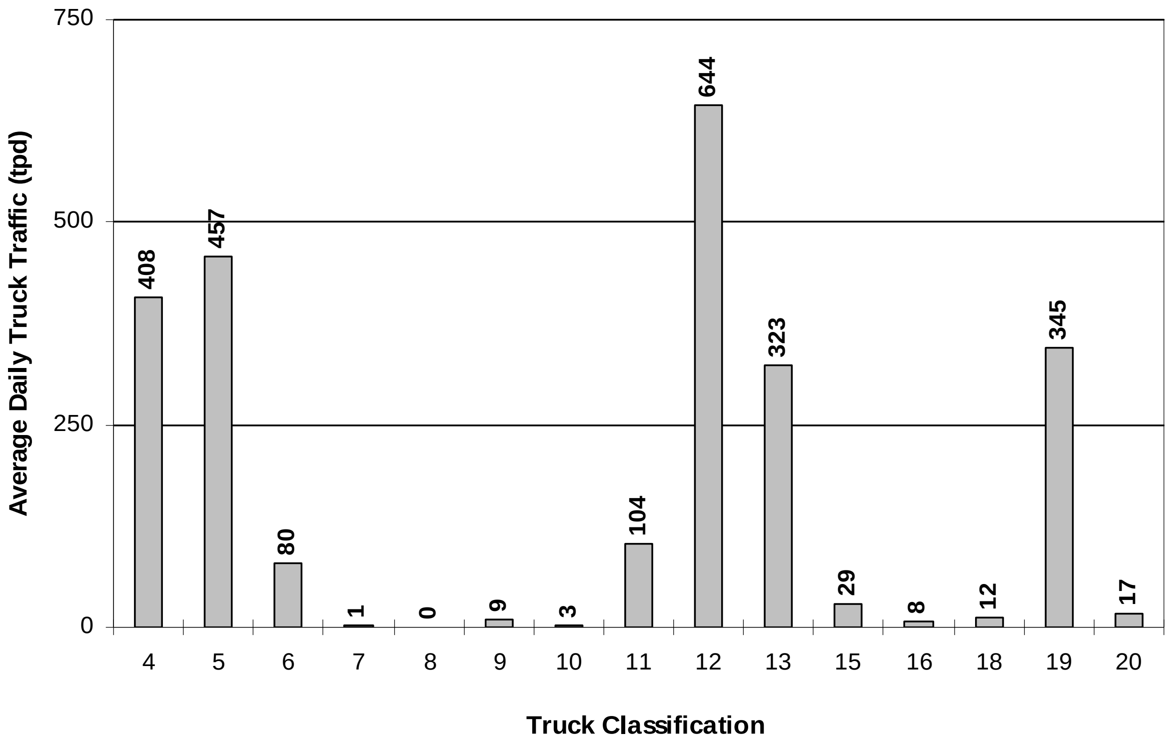


**Figure 4.1 – Distribution of Average Daily Truck Population across all Lanes**

The seven main truck configurations contributed 97 percent of the total truck population observed over the seven day study period. Due to the large presence of the Class 4, 5, 6, 11, 12, 13 and 19 truck configurations in the data records, the commercial vehicle spectra analysis was completed only for these seven configurations. It was assumed that these configurations would exhibit the major loading trends at the study site because they represented the majority of the population. Table 4.2 summarizes the total number of truck records analyzed in this study based on this assumption.

**Table 4.2 - Truck Traffic Records for Seven Main Configurations**

| Date | Total Truck Records |
|---|---|
| Friday, May 12, 2006 | 3,288 |
| Saturday, May 13, 2006 | 1,533 |
| Sunday, May 14, 2006 | 871 |
| Monday, May 15, 2006 | 3,295 |
| Tuesday, May 16, 2006 | 3,212 |
| Wednesday, May 17, 2006 | 3,268 |
| Thursday, May 18, 2006 | 1,058 |
| Total Recorded Trucks | 16,525 |

Table 4.3 and Figure 4.2 illustrate the distribution of the seven major truck configurations across each lane. A total of 43 percent of observed trucks traveled in the westbound curb lane and 34 percent traveled in the eastbound curb lane, equating to 77 percent of all observed vehicles. The directional split of the data sample was approximately 50/50 between the eastbound and westbound directions of travel, as summarized in Table 4.3.

**Table 4.3 - Analysis Period Count Data**

| | EBCL | EBML | WBML | WBCL | Total WB | Total EB | Total All Directions |
|---|---|---|---|---|---|---|---|
| Class 4 | 1,177 | 461 | 208 | 1,008 | 1,216 | 1,638 | 2,854 |
| Class 5 | 978 | 650 | 296 | 1,274 | 1,570 | 1,628 | 3,198 |
| Class 6 | 67 | 20 | 34 | 439 | 473 | 87 | 560 |
| Class 11 | 205 | 113 | 74 | 335 | 409 | 318 | 727 |
| Class 12 | 1,544 | 611 | 312 | 2043 | 2,355 | 2,155 | 4,510 |
| Class 13 | 702 | 398 | 169 | 992 | 1,161 | 1,100 | 2,261 |
| Class 19 | 876 | 377 | 156 | 1,006 | 1,162 | 1,253 | 2,415 |
| TOTAL | 5,549 | 2,630 | 1,249 | 7,097 | 8,346 | 8,179 | 16,525 |
| TOTAL | 33.6 % | 15.9 % | 7.6 % | 42.9 % | 50.5 % | 49.5 % | 100 % |

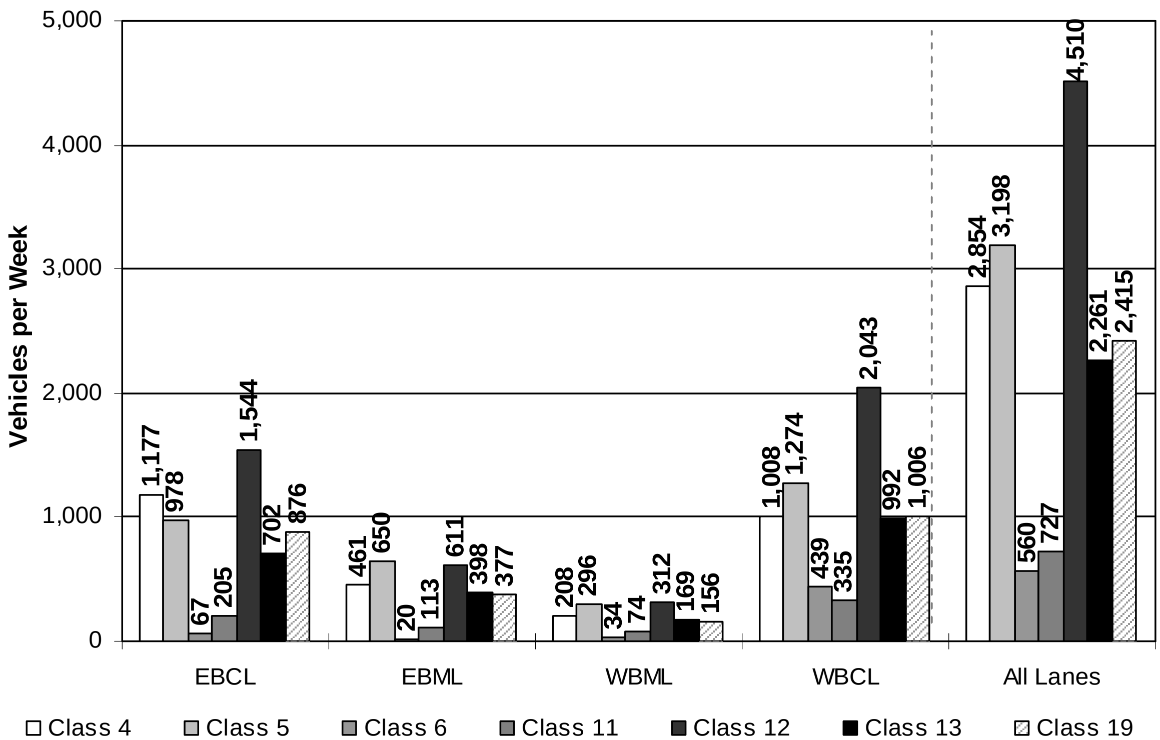


**Figure 4.2 - Total Seven-Day Vehicle Count by Lane and Class**

The average and maximum GVW for the seven configurations are summarized in Table 4.4 and Figure 4.3. Analysis of the average GVW by configuration found that vehicles were typically largest in the eastbound curb lane. However, the eastbound median lane was found to carry the lightest vehicles based on average GVW by class, with the exception of Class 4, 6 and

11 vehicles. Class 4, 6 and 11 vehicles were, however, the lightest in the westbound direction, with average GVW of 8, 27 and 9 percent below their average GVW for all lanes.

As shown in Table 4.4 and Figure 4.3, the maximum GVW records ranged from 170 percent greater than the average Class 19 GVW to 490 percent greater than the average Class 6 GVW. The complete count and GVW analysis tables are available in Appendix D.

**Table 4.4 - Average and Maximum GVW by Class**

| Vehicle Class | EBCL | | EBML | | WBML | | WBCL | | All Lanes | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Avg. (kg) | Max (kg) | Avg. (kg) | Max (kg) | Avg. (kg) | Max (kg) | Avg. (kg) | Max (kg) | Avg. (kg) | Max (kg) |
| Class 4 | 10,139 | 22,728 | 9,645 | 18,113 | 8,971 | 15,194 | 9,508 | 20,405 | 9,738 | 22,728 |
| Class 5 | 16,821 | 32,006 | 13,939 | 31,464 | 15,052 | 36,124 | 16,660 | 38,242 | 14,689 | 38,242 |
| Class 6 | 25,707 | 44,119 | 20,921 | 35,079 | 11,918 | 23,640 | 7,108 | 47,616 | 9,717 | 47,616 |
| Class 11 | 11,085 | 28,230 | 9,777 | 34,992 | 9,364 | 32,369 | 10,222 | 31,640 | 10,309 | 34,992 |
| Class 12 | 26,585 | 47,033 | 19,259 | 43,410 | 25,336 | 43,657 | 27,066 | 46,466 | 26,295 | 47,033 |
| Class 13 | 31,895 | 53,574 | 22,628 | 50,484 | 27,943 | 47,481 | 31,727 | 56,261 | 29,975 | 56,261 |
| Class 19 | 44,991 | 75,572 | 33,217 | 68,121 | 39,956 | 64,665 | 45,234 | 69,892 | 44,068 | 75,572 |

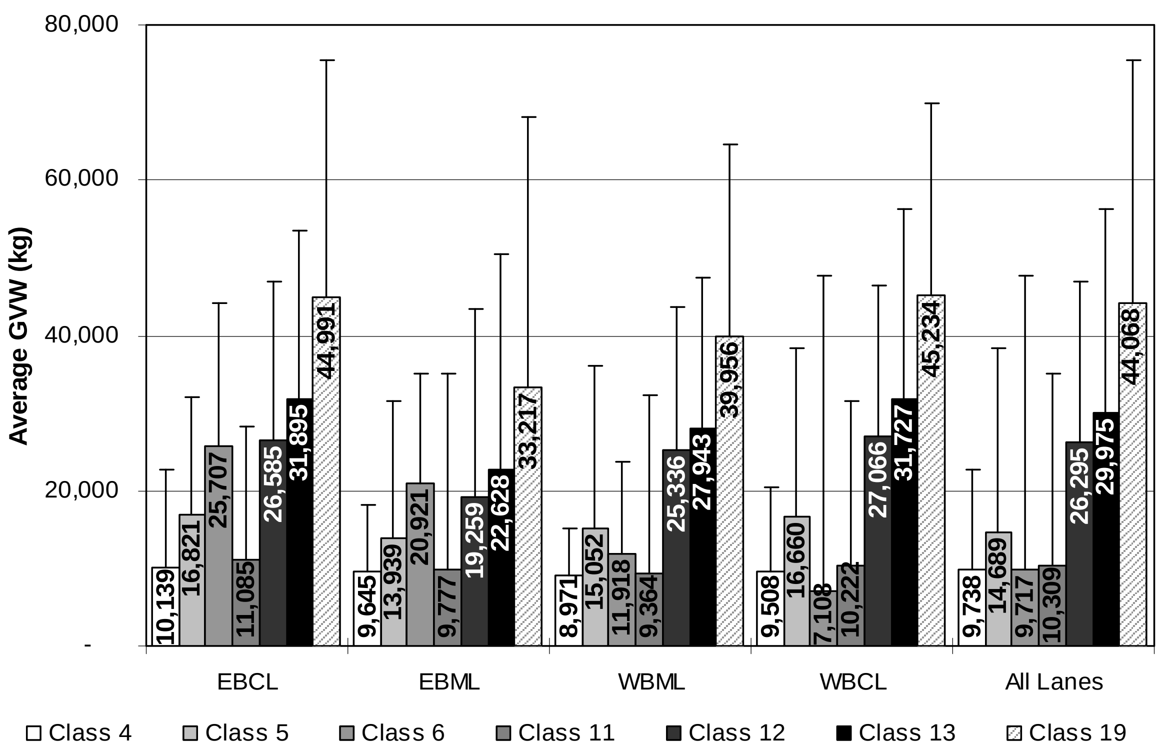


**Figure 4.3 –Average and Maximum GVW by Lane and Class**

Analysis of the average and maximum axle group loads by configuration is presented in Table 4.5 and Figure 4.4. The average steering axle group weights for each vehicle configuration were fairly consistent within each class and ranged from 2,538 kg for Class 11 to 5,809 kg for Class 5. Analysis of the maximum steering axle weights showed that the straight truck configurations (Classes 4, 5 and 6) typically had higher variances within their weights and higher maximum weights than the other vehicle configurations. The maximum steering axle weights ranged from 6,441 kg for Class 19 to 24,648 kg for Class 6.

The drive axle groups exhibited similar trends to the steering axle groups, whereby Class 5 and 6 vehicles, despite their lower average weights, had higher maximum drive axle group weights. The maximum drive axle weights ranged from 13,175 kg for Class 4 to 25,075 kg for Class 6.

The trailer tridem and tandem axle weights were similar between Class 13 and 19, and Class 12 and 19. However, Class 19 tandem and tridem axle groups were generally heavier than their Class 12 and 13 counterparts. Similarities between loading trends were expected for Class 12, 13 and 19 trailer axle groups since their axle configurations and trailer units are comparable. The maximum trailer axle weights ranged from 20,693 kg for the Class 11 trailer tandem to 31,642 kg for the Class 13 trailer tridem. Class 11 vehicles had a maximum weight similar to the Class 12 and 19 trailer tandem axle maximum but with a much lower average GVW. The lower average GVW was most likely due to the existence of a specialized commodity range for the Class 11 configuration as compared to the other two configurations.

**Table 4.5 - Average and Maximum Axle Group Weights by Vehicle Class**

| | Steer | | Drive | | Trailer Tridem | | Trailer Tandem | |
|---|---|---|---|---|---|---|---|---|
| | Avg. (kg) | Max (kg) | Avg. (kg) | Max (kg) | Avg. (kg) | Max (kg) | Avg. (kg) | Max (kg) |
| Class 4 | 3,797 | 11,239 | 5,981 | 13,175 | - | - | - | - |
| Class 5 | 5,098 | 11,525 | 8,897 | 23,866 | - | - | - | - |
| Class 6 | 4,924 | 24,648 | 4,792 | 25,075 | - | - | - | - |
| Class 11 | 2,538 | 7,713 | 3,673 | 13,250 | - | - | 4,098 | 20,693 |
| Class 12 | 4,899 | 7,751 | 11,879 | 22,275 | - | - | 10,711 | 23,399 |
| Class 13 | 4,732 | 8,158 | 11,815 | 21,926 | 14,287 | 31,642 | - | - |
| Class 19 | 4,887 | 6,441 | 13,104 | 21,042 | 16,615 | 28,458 | 12,124 | 22,862 |

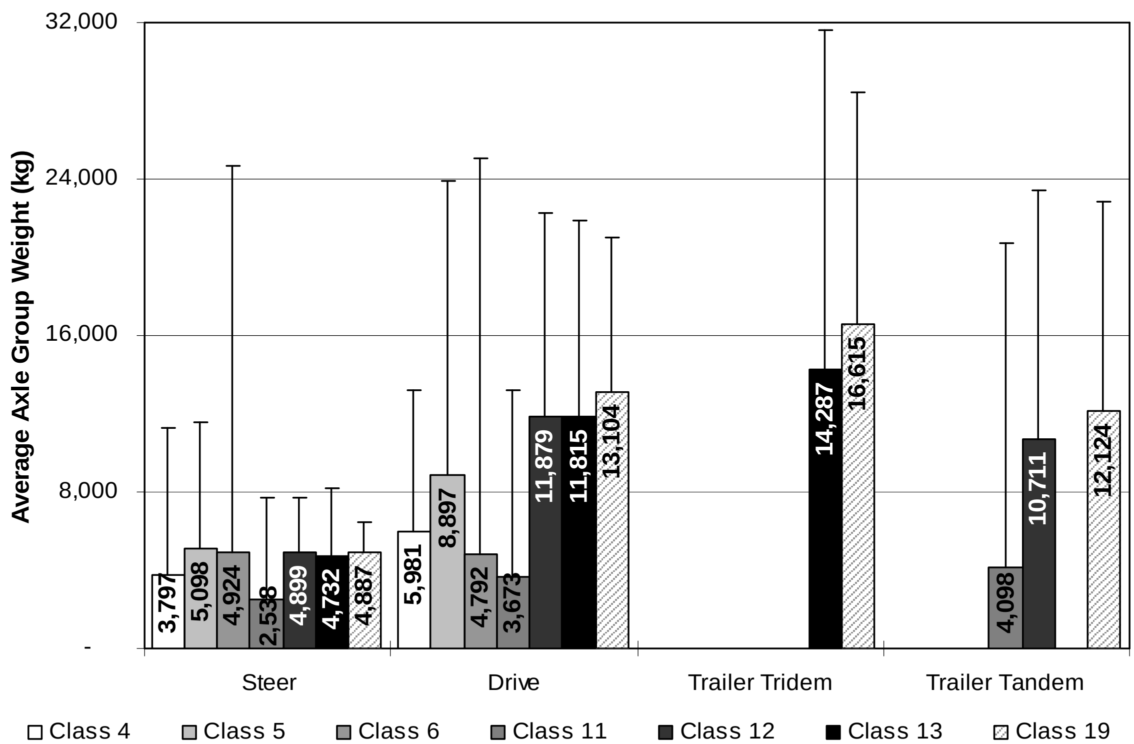


**Figure 4.4 – Average and Maximum Axle Group Weights by Vehicle Class**

## 4.2 Equivalent Single Axle Load Analysis

A terminal serviceability of 2.5 and structural number of 2 were utilized to represent the road structure at the Circle/Preston VWIM site. GVW and axle group ESALs were assessed across the seven vehicle configurations captured during the seven-day analysis period. Best-fit equations were utilized to represent AASHTO ESALFs for the single, tandem and tridem axle groups. Full ESAL analysis tables are located in Appendix E.

Given that the vehicle distribution indicated that most of the vehicles traveled in the curb lanes, only the curb lanes for either direction of travel were assessed. An upper one-tailed analysis was completed to determine the range of the ESALs within the observed truck populations, as represented by mean and 95$^{th}$ percentile probability bands.

Table 4.6 and Figure 4.5 summarize the GVW ESALs for each of the major truck configurations in the westbound and eastbound curb lanes. With the exception of the Class 6 and 11 configurations, both directions exhibited an increase in both the mean GVW ESALs and 95$^{th}$ percentile probability bands as truck size increased from Class 4 to Class 19. The Class 11 configuration exhibited the lowest GVW ESALs for both directions as compared to the other semi-trailer units. The westbound Class 6 configuration, which is typically representative of large concrete trucks, exhibited similar GVW ESAL trends to those observed for the Class 4 and 5 configurations. The eastbound Class 6 configuration had high GVW ESALs with mean load and probability bands similar to those obtained for Class 19 vehicles. This indicated that more of the eastbound tandem steering straight trucks were loaded as compared to those traveling westbound.

**Table 4.6 –Analysis of Mean GVW ESAL Loads**

| GVW ESALs | Class 4 | Class 5 | Class 6 | Class 11 | Class 12 | Class 13 | Class 19 |
|---|---|---|---|---|---|---|---|
| **WESTBOUND CURB LANE** | | | | | | | |
| Mean | 0.831 | 1.164 | 0.382 | 0.373 | 1.813 | 1.687 | 3.380 |
| 95$^{th}$ | 3.201 | 3.866 | 2.230 | 2.473 | 4.720 | 4.412 | 7.364 |
| **EASTBOUND CURB LANE** | | | | | | | |
| Mean | 0.995 | 1.201 | 2.456 | 0.440 | 1.435 | 1.708 | 3.121 |
| 95$^{th}$ | 3.312 | 3.362 | 5.843 | 1.756 | 4.049 | 4.537 | 7.844 |

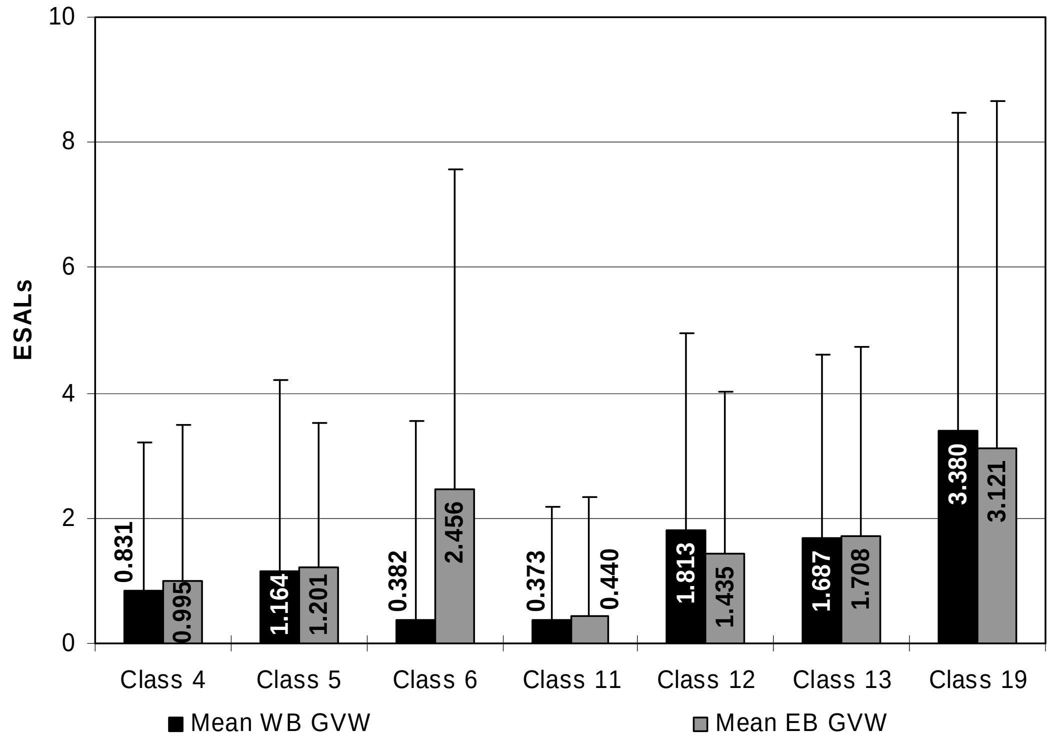


**Figure 4.5 – Mean Westbound and Eastbound GVW ESALs (+ 95$^{th}$ Percentile)**

A total of 11,420 GVW ESALs were observed across the seven vehicle configurations in the westbound curb lane during the seven day study period, as presented in Table 4.7 and Figure 4.6. As seen in Table 4.7, most of the westbound GVW ESALs were contributed by Class 12 and 19 vehicles, which generated approximately 30 percent of the GVW ESALs each. It was also noted that Class 12 and 19 vehicles contributed more than half of the total drive axle ESALs, and that Class 5 vehicles contributed most of the steer axle ESALs. A total of 2,561 steering axle ESALs were recorded within the westbound curb lane, with 33 percent contributed by Class 5 vehicles and 30 percent contributed by Class 12 vehicles. The higher representation of Class 5 and Class 12 vehicles in the cumulative ESAL distribution was anticipated since both classes had the greatest presence within the observed population, at 20 percent and 33 percent.

**Table 4.7 –Cumulative Westbound Curb Lane ESALs by Vehicle Class**

| ESAL Distribution | Class 4 | Class 5 | Class 6 | Class 11 | Class 12 | Class 13 | Class 19 | All Classes |
|---|---|---|---|---|---|---|---|---|
| GVW | 837 | 1,482 | 168 | 156 | 3,704 | 1,673 | 3,401 | 11,420 |
| Steering Axle | 152 | 845 | 84 | 35 | 764 | 327 | 355 | 2,561 |
| Drive Axle | 685 | 637 | 84 | 94 | 1,514 | 774 | 1,138 | 4,926 |
| Trailer Tridem | - | - | - | - | - | 572 | 800 | 1,372 |
| Trailer Tandem | - | - | - | 27 | 1,426 | - | 1,108 | 2,561 |
| GVW (%) | 7.3 | 13.0 | 1.5 | 1.4 | 32.4 | 14.6 | 29.8 | 100 |
| Steering Axle (%) | 5.9 | 33.0 | 3.3 | 1.4 | 29.8 | 12.8 | 13.9 | 100 |
| Drive Axle (%) | 13.9 | 12.9 | 1.7 | 1.9 | 30.7 | 15.7 | 23.1 | 100 |
| Trailer Tridem (%) | - | - | - | - | - | 41.7 | 58.3 | 100 |
| Trailer Tandem (%) | - | - | - | 1.0 | 55.7 | - | 43.3 | 100 |

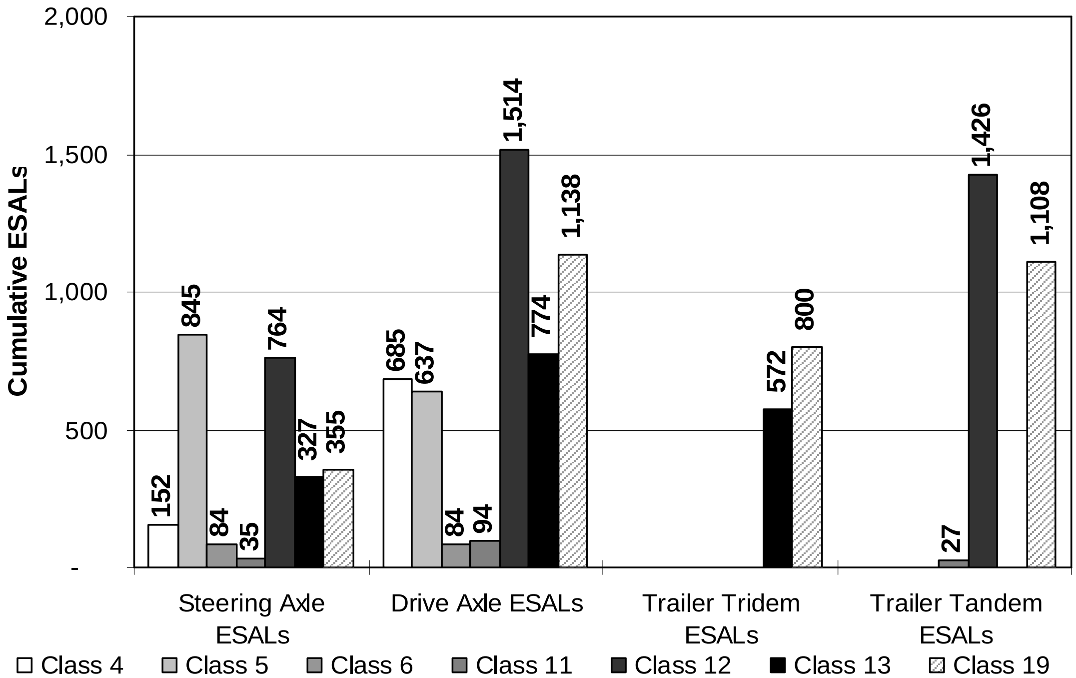


**Figure 4.6 - Cumulative Seven Day Westbound ESALs**

The eastbound curb lane ESAL spectra are summarized in Table 4.8 and Figure 4.7. A total of 8,860 GVW ESALs were observed during the seven-day analysis period. The majority of the eastbound GVW ESALs were contributed by Class 12 and 19 configurations, at 25 and 31 percent of the total eastbound ESALs. As seen in Figure 4.7, Class 4, 12 and 19 vehicles contributed most of the drive axle ESALs, at 22, 21 and 23 percent of the total drive axle ESALs.

Most of the steering axle ESALs were contributed by Class 5 and 12 vehicles, as would be expected due to their larger mean steering axle loads and their greater presence in the observed traffic stream. A total of 2,224 ESALs were recorded for the steering axle group, of which Class 5 and 12 vehicles contributed more than half of the recorded loads.

**Table 4.8 –Cumulative Eastbound Curb Lane ESALs by Vehicle Class**

| ESAL Distribution | Class 4 | Class 5 | Class 6 | Class 11 | Class 12 | Class 13 | Class 19 | All Classes |
|---|---|---|---|---|---|---|---|---|
| GVW | 1,171 | 1,286 | 165 | 90 | 2,215 | 1,199 | 2,734 | 8,860 |
| Steering Axle | 268 | 618 | 88 | 15 | 606 | 248 | 381 | 2,224 |
| Drive Axle | 903 | 668 | 76 | 68 | 893 | 595 | 968 | 4,171 |
| Trailer Tridem | - | - | - | - | - | 356 | 690 | 1,046 |
| Trailer Tandem | - | - | - | 7 | 717 | - | 694 | 1,418 |
| GVW (%) | 13.2 | 14.5 | 1.9 | 1.0 | 25.0 | 13.5 | 30.9 | 100 |
| Steering Axle (%) | 12.1 | 27.8 | 4.0 | 0.7 | 27.2 | 11.2 | 17.1 | 100 |
| Drive Axle (%) | 21.6 | 16.0 | 1.8 | 1.6 | 21.4 | 14.3 | 23.2 | 100 |
| Trailer Tridem (%) | - | - | - | - | - | 34.0 | 66.0 | 100 |
| Trailer Tandem (%) | - | - | - | 0.5 | 50.6 | - | 48.9 | 100 |

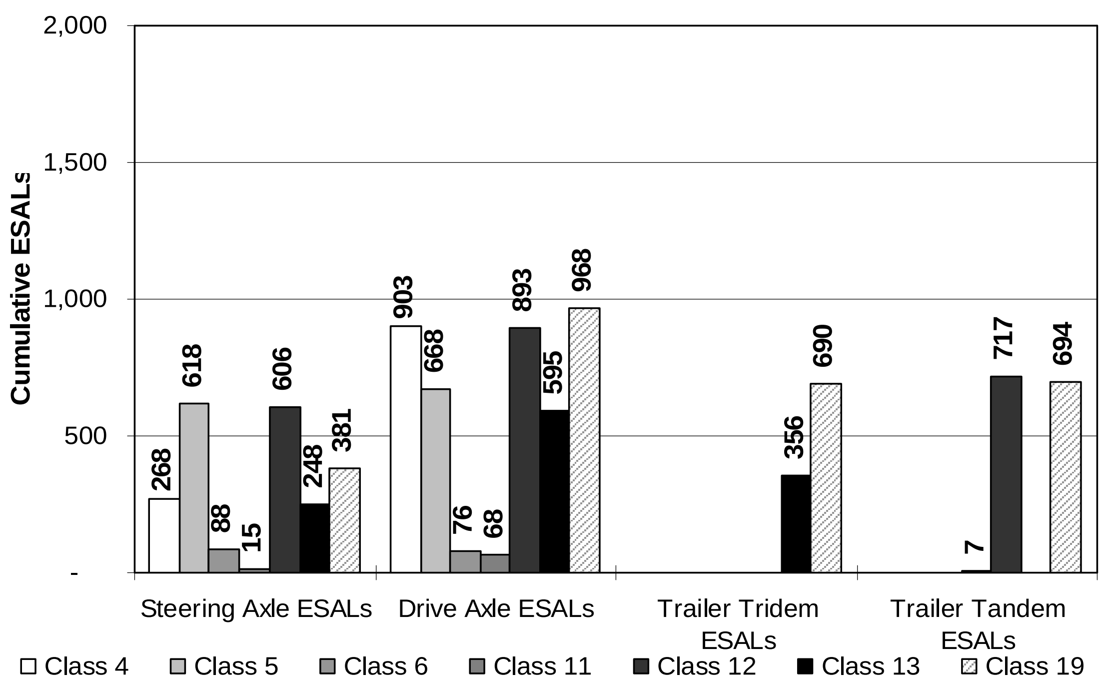


**Figure 4.7 – Cumulative Seven Day Eastbound ESALs**

The cumulative GVW ESALs for the westbound and eastbound curb lanes are summarized by vehicle configuration in Figure 4.8. As seen in Figure 4.8, 30 percent of the cumulative GVW ESALs were contributed by Class 19 vehicles and 29 percent were contributed by Class 12 vehicles. Class 5 and 13 vehicles contributed to 14 percent of the total cumulative GVW ESALs each.

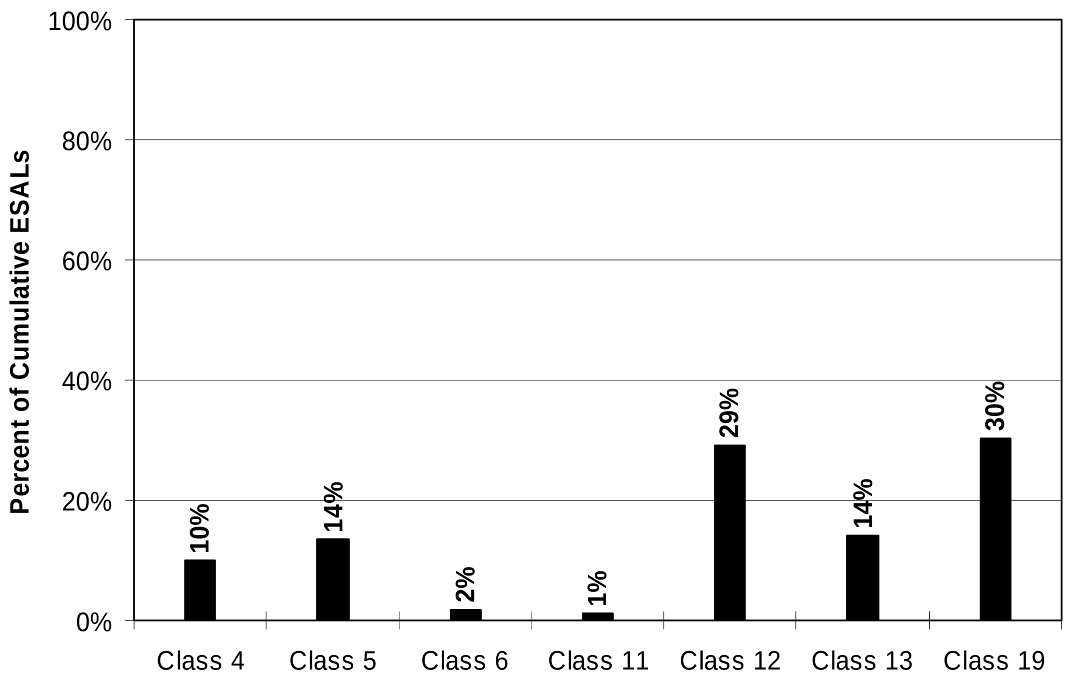


**Figure 4.8 - Cumulative Seven Day Westbound and Eastbound GVW ESALs by Class**

Assessment of the vehicle distribution by lane, as presented in Figure 4.9, indicated that Class 12 vehicles contributed to the largest portion of the observed population at 27 percent. Class 19 vehicles were the fourth largest contributor to the observed population at 15 percent, trailing behind Class 4 and 5 vehicles, which contributed to 17 and 19 percent of the observed seven configuration population. The westbound curb lane contained nearly half of the vehicles observed during the seven day study period and 78 percent of the Class 6 configurations.

The large amount of cumulative GVW ESALs contributed by Class 12 vehicles was anticipated due to the large presence of this vehicle class within the observed traffic stream. In addition, the high amount of cumulative GVW ESALs contributed by the Class 19 configuration was representative of its larger truck size as compared to the other truck types in this analysis.

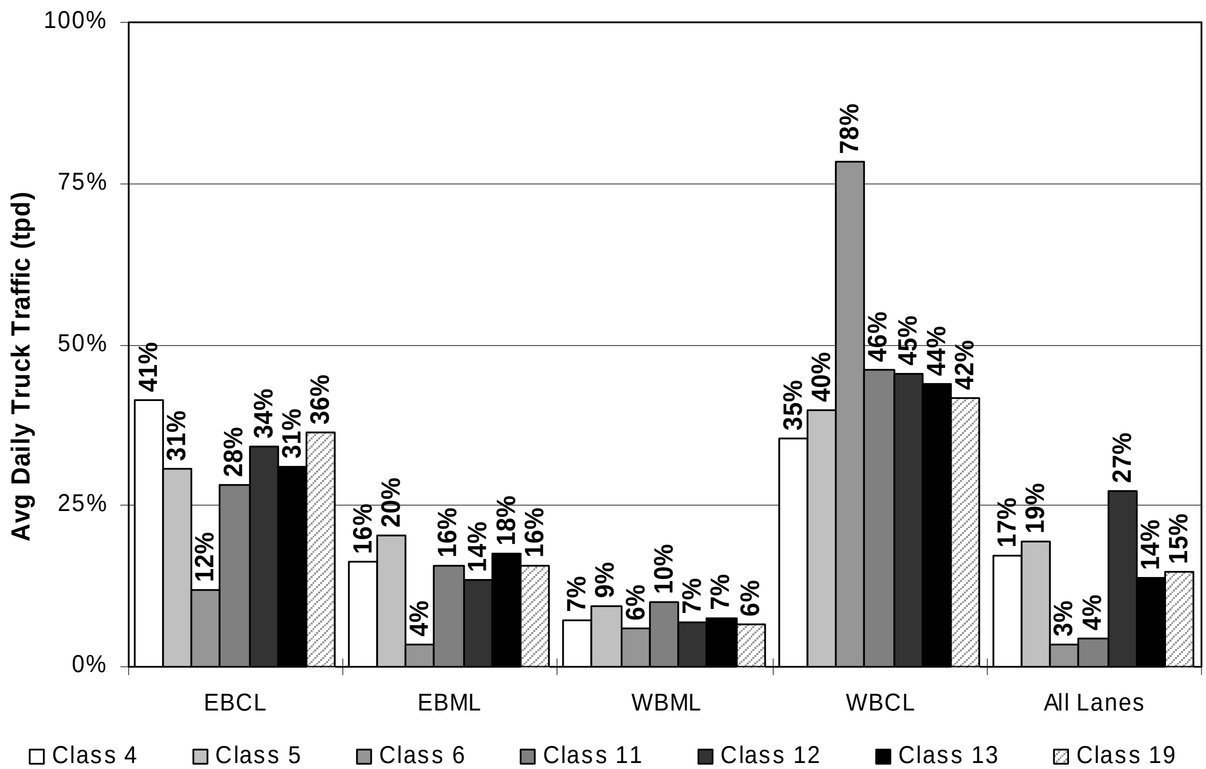


**Figure 4.9 - Vehicle Representation by Lane and by Class**

### 4.2.1 Class 4 Vehicle Load Analysis

The Class 4 vehicle configuration contributed to 17 percent of the observed population during the seven day, seven configuration analysis. Class 4 vehicles represent two axle straight trucks and generally consist of intra-city delivery trucks and construction vehicles (such as delivery and gravel trucks), as illustrated in Figure 4.10. This configuration also consists of school and urban public transit buses, as illustrated in Figure 4.11.


**Figure 4.10 – Two Axle Straight Truck, City of Saskatoon**


**Figure 4.11 – CLASSIC Bus, City of Saskatoon**

The distribution of westbound and eastbound Class 4 GVW ESALs by truck record is illustrated in Figure 4.12. The majority of Class 4 GVW records in both directions ranged from 1 to 2 ESALs. As shown in Figure 4.12, eastbound Class 4 GVW records were slightly heavier than westbound GVW records. The legal weight limit for Class 4 vehicles equated to 2.8 GVW ESALs per vehicle on this roadway.

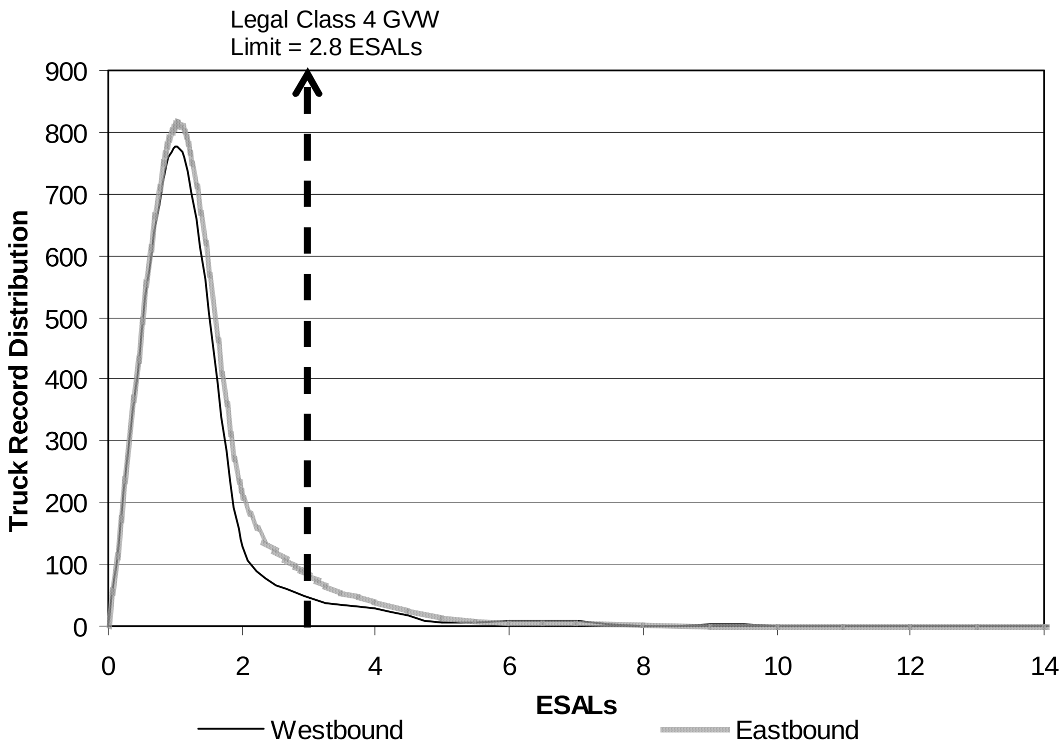


**Figure 4.12 - Distribution of Westbound and Eastbound Class 4 GVW Records**

The average GVW for westbound Class 4 vehicles was 0.83 ESALs, with most of the average load contributed by the drive axle group, as illustrated in Figure 4.13. Comparison of the 95th percentile probability bands for the axle group and GVW ESALs indicated that the steering axle group had a minor effect on the GVW ESALs for the westbound Class 4 vehicle. The mean GVW for eastbound Class 4 vehicles was 0.99 ESALs, with the majority being contributed by the drive axle group, as summarized in Table 4.9 and Figure 4.13.

**Table 4.9 - Westbound and Eastbound Class 4 Mean ESALs**

| | GVW ESALs | Steering Axle ESALs | Drive Axle ESALs |
|---|---|---|---|
| **WESTBOUND CURB LANE** | | | |
| Mean Load | 0.83 | 0.15 | 0.68 |
| 95th Percentile | 3.20 | 0.39 | 2.88 |
| **EASTBOUND CURB LANE** | | | |
| Mean Load | 0.99 | 0.23 | 0.77 |
| 95th Percentile | 3.31 | 0.72 | 2.77 |

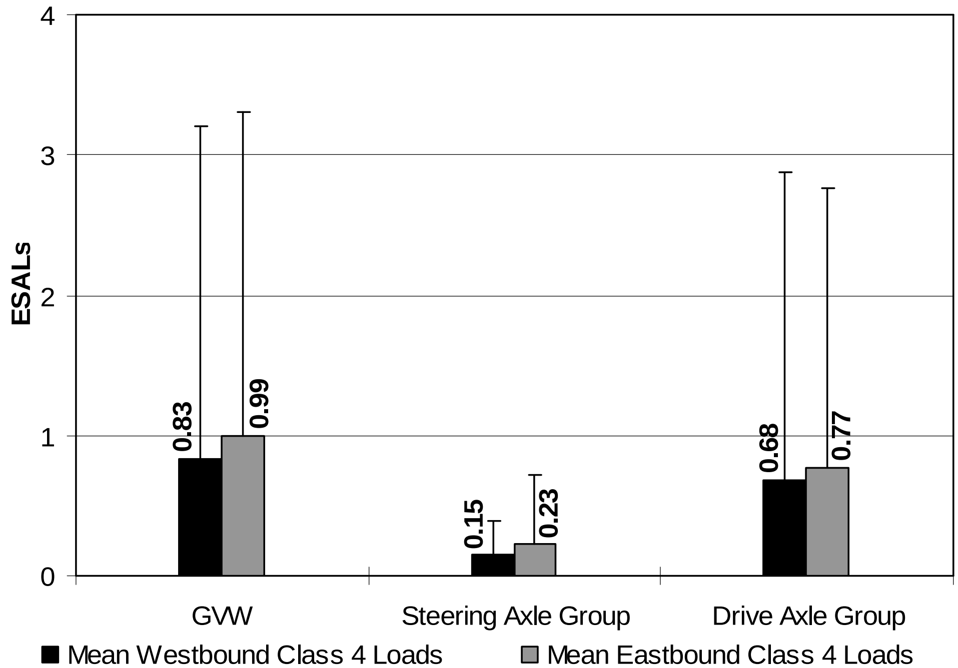


**Figure 4.13 – Westbound and Eastbound Class 4 Mean ESALs (+ 95th Percentile)**

As seen in Figure 4.14, the Class 4 steering axle group contributed less than one quarter of the total cumulative ESALs for the westbound and eastbound directions of travel.

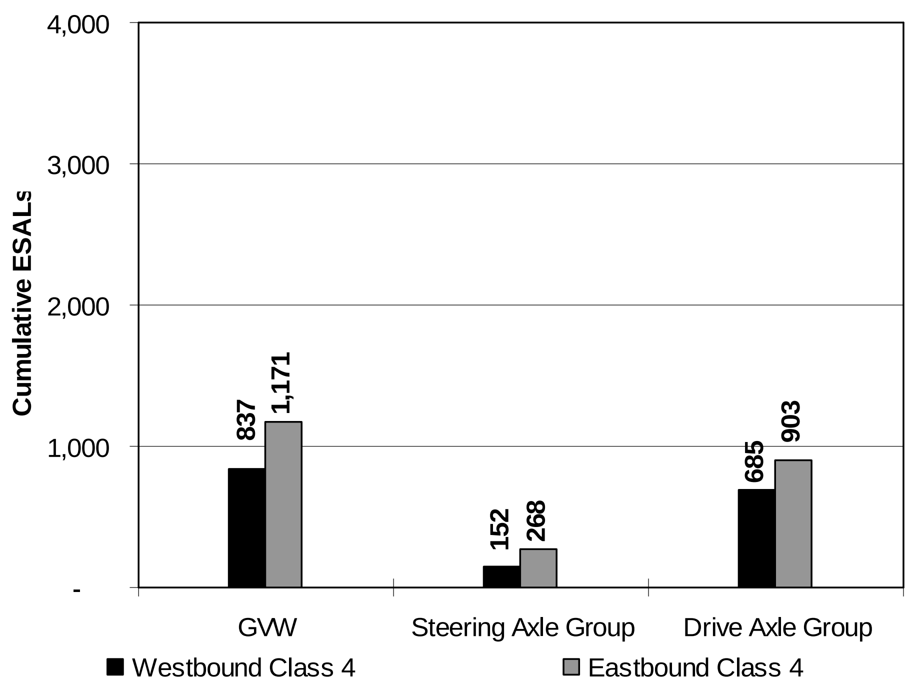


**Figure 4.14 - Westbound and Eastbound Class 4 Cumulative Seven Day ESALs**

### 4.2.2 Class 5 Vehicle Load Analysis

The Class 5 vehicle configuration contributed to 19 percent of the population from the seven day, seven configuration analysis. This configuration represents three axle straight trucks and generally consists of large gravel trucks, small cement trucks, and municipal waste collection vehicles, as illustrated in Figure 4.15.


**Figure 4.15 – Municipal Waste Collection Vehicle, City of Saskatoon**

The distribution of westbound and eastbound Class 5 GVW ESALs is illustrated in Figure 4.16. The majority of Class 5 GVW records in both directions of travel ranged from 1 to 2 ESALs. As shown in Figure 4.16, eastbound Class 5 GVW records were slightly lighter than westbound GVW records. The legal weight limit for Class 5 vehicles equated to 3 GVW ESALs per vehicle on this roadway.

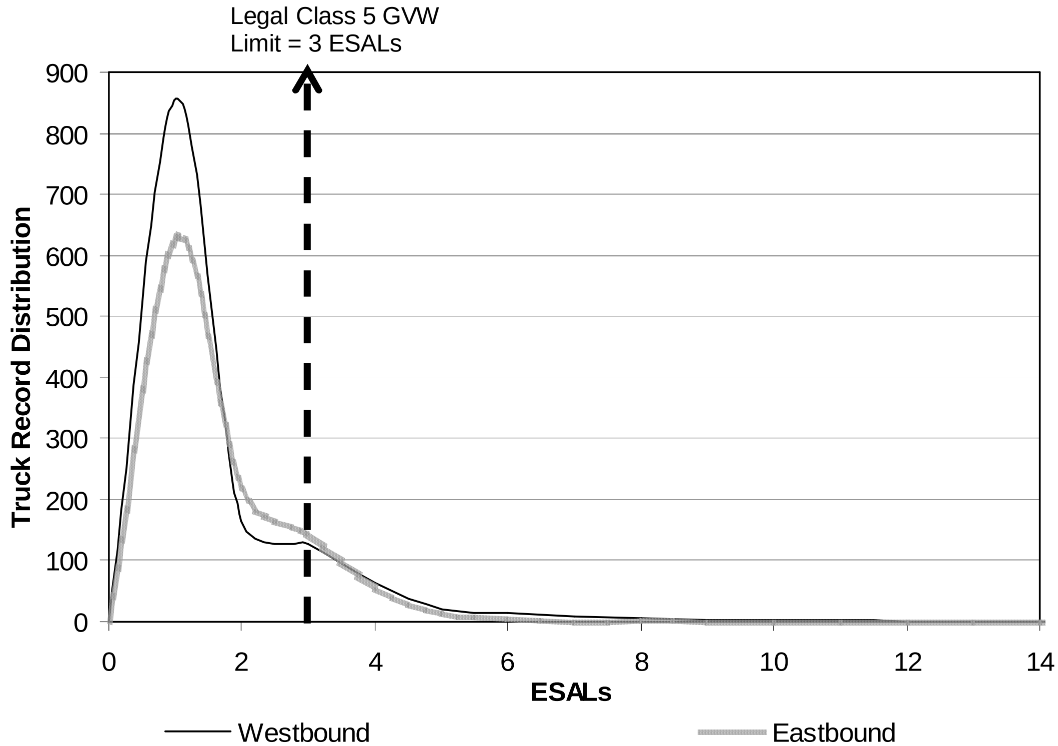


**Figure 4.16 - Distribution of Westbound and Eastbound Class 5 GVW Records**

Class 5 vehicles exhibited high variability within the steering and drive axle ESALs, as summarized in Table 4.10 and Figure 4.17. This indicated that there was less uniformity among Class 5 commodities and that a large amount of weight variability, possibly due to overloading, was occurring. The steering axle group has fewer tires (two instead of four) than others and less surface area through which to distribute excess load. As such, a small increase in steering axle weight can produces a more pronounced increase in ESALs than would occur for a typical four-tired AASHTO axle groups (single, double and triple).

Table 4.10 - Westbound and Eastbound Class 5 Mean ESALs

| | GVW ESALs | Steering Axle ESALs | Drive Axle ESALs |
|---|---|---|---|
| **WESTBOUND CURB LANE** | | | |
| Mean Load | 1.16 | 0.66 | 0.50 |
| 95$^{th}$ Percentile | 3.87 | 2.32 | 2.36 |
| **EASTBOUND CURB LANE** | | | |
| Mean Load | 1.20 | 0.58 | 0.62 |
| 95$^{th}$ Percentile | 3.36 | 1.80 | 2.26 |

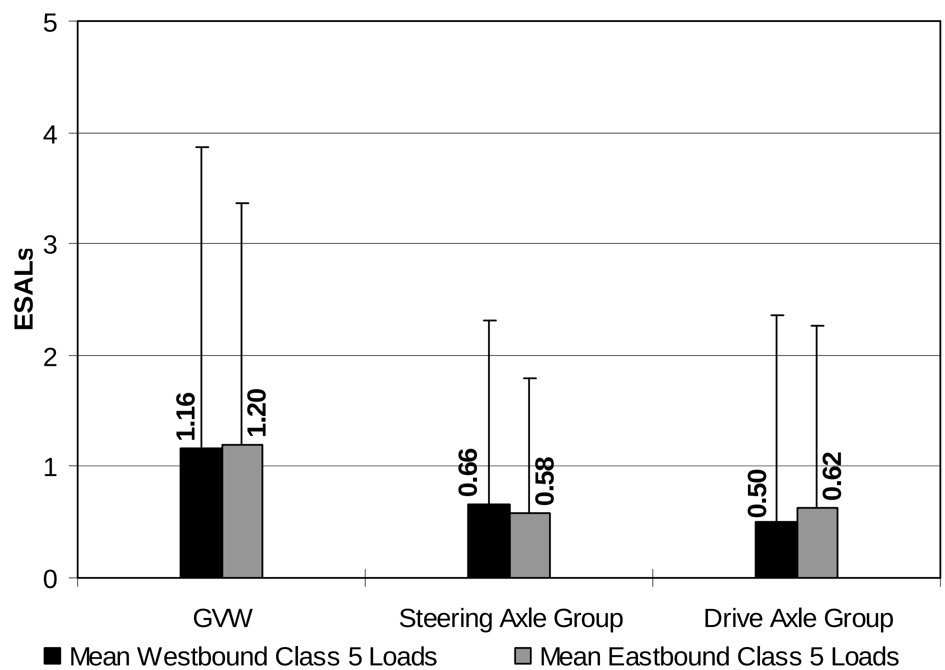


**Figure 4.17 - Westbound and Eastbound Class 5 Mean ESALs (+ 95$^{th}$ Percentile)**

The cumulative ESALs contributed by the Class 5 steering axle group, illustrated in Figure 4.18, were nearly equivalent to those contributed by the drive axle group. The likeness between steering axle and drive axle cumulative ESALs could be related to more frequent overloading within the vehicle class or to variations within the vehicle commodity causing dispersion of load. As seen in Figure 4.18, the steering axle group contributed 57 and 48 percent of the cumulative ESALs for the westbound and eastbound curb lanes.

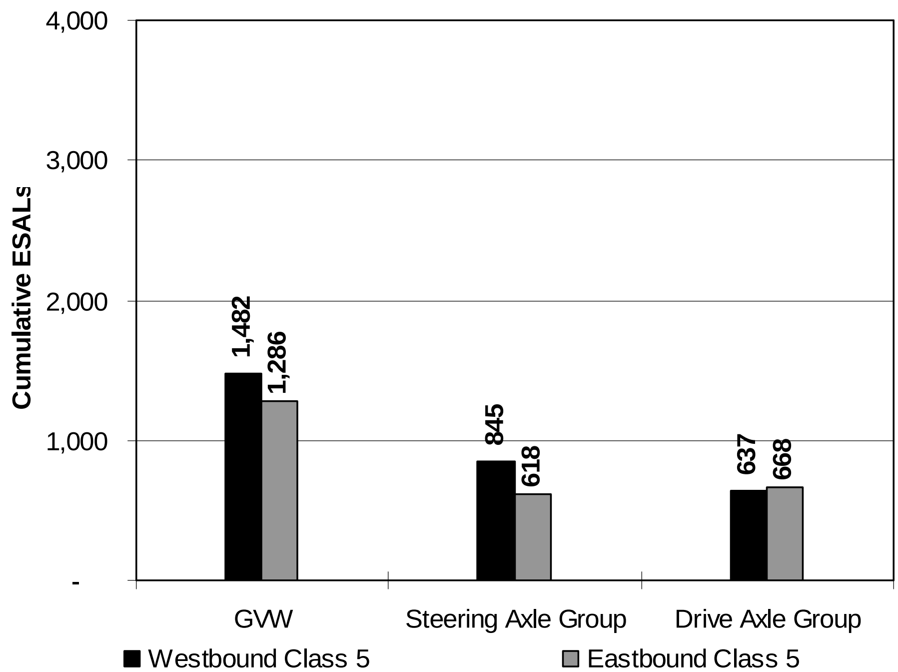


**Figure 4.18 - Westbound and Eastbound Class 5 Cumulative Seven Day ESALs**

### 4.2.3 Class 6 Vehicle Load Analysis

The Class 6 vehicle designation contributed 3.4 percent of the population observed in the seven day analysis. This configuration represents four axle straight trucks with tandem steering, commonly representing large concrete trucks.

The distribution of westbound and eastbound Class 6 GVW ESALs is illustrated in Figure 4.19. Analysis of the Class 6 GVW ESAL distribution indicated directional differences in loading magnitude. These differences were due to loaded vs. unloaded trips, and may have been exacerbated by the combination of overloading and fewer vehicle records in the eastbound direction of travel.

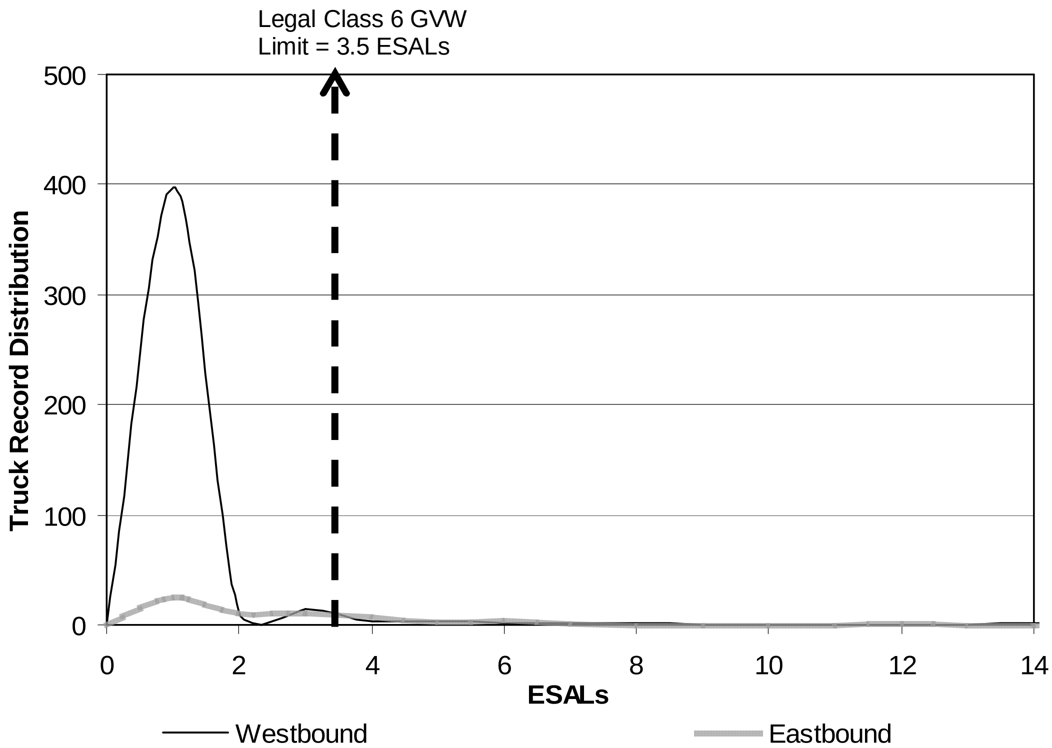


**Figure 4.19 - Distribution of Westbound and Eastbound Class 6 GVW Records**

As seen in Table 4.11 and Figure 4.20, westbound Class 6 vehicles were typically lighter than those traveling eastbound. However, despite the directional loading differences, the cumulative Class 6 ESALs, illustrated in Figure 4.21, were similar for either direction. The even load distribution between axle groups was due to the very small eastbound population, where 67 vehicles were observed traveling eastbound and 439 traveling westbound.

**Table 4.11 - Westbound and Eastbound Class 6 Mean ESALs**

| | GVW ESALs | Steering Axle ESALs | Drive Axle ESALs |
|---|---|---|---|
| **WESTBOUND CURB LANE** | | | |
| Mean Load | 0.38 | 0.19 | 0.19 |
| 95th Percentile | 2.23 | 1.13 | 0.94 |
| **EASTBOUND CURB LANE** | | | |
| Mean Load | 2.46 | 1.32 | 1.14 |
| 95th Percentile | 5.84 | 3.86 | 2.86 |

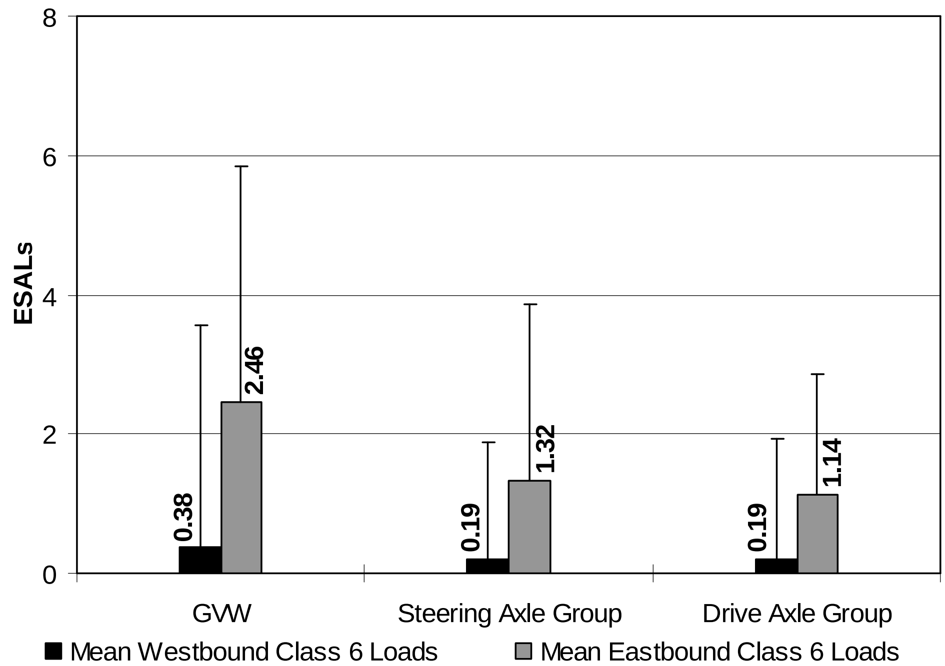


**Figure 4.20 - Westbound and Eastbound Class 6 Mean ESALs (+ 95th Percentile)**

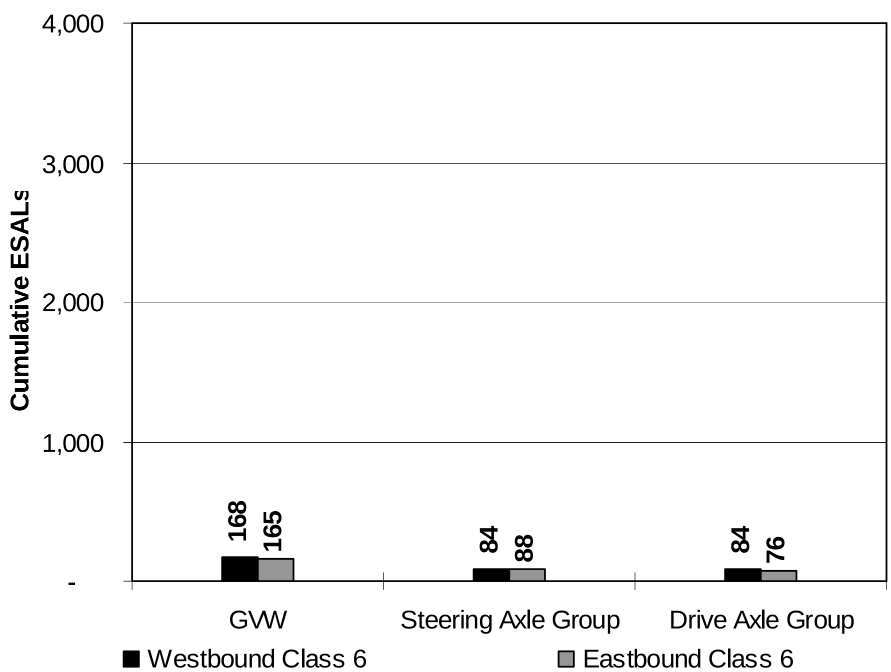


**Figure 4.21 - Westbound and Eastbound Class 6 Cumulative Seven Day ESALs**

### 4.2.4 Class 11 Vehicle Load Analysis

The Class 11 configuration contributed to 4.4 percent of the population in the seven day, seven configuration study. This configuration represents four axle trucks with single drive axle groups and full tandem trailers.

The Class 11 GVW ESALs is illustrated in Figure 4.22. The Class 11 GVW ESALs showed exaggerated distributions in the westbound direction due to a greater number of vehicle records. Additionally, a slight tendency towards heavier westbound loads was noted due to the presence of a secondary peak around the legal weight limit.

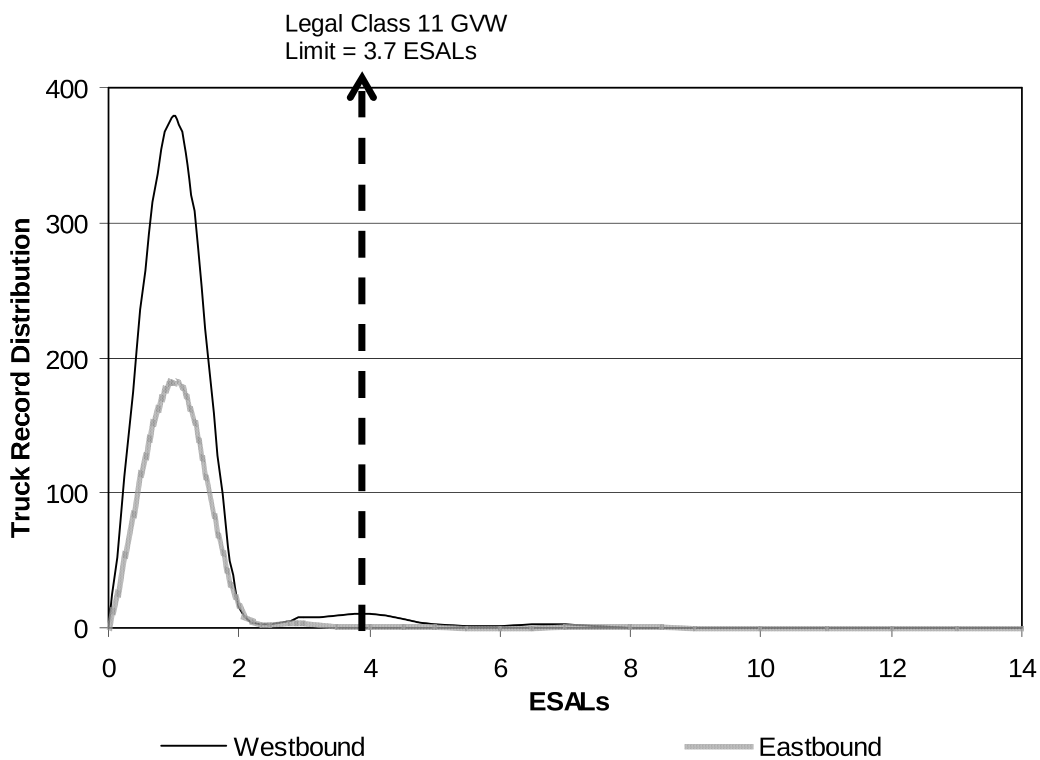


**Figure 4.22 - Distribution of Westbound and Eastbound Class 11 GVW Records**

The Class 11 ESAL analysis, presented in Table 4.12 and Figure 4.23, exhibited smaller mean GVW ESALs as compared to the other configurations. Westbound Class 11 vehicles exhibited high variability within the drive axle groups, and the eastbound vehicles exhibited high variability within both the drive and trailer tandem axle groups. Higher variability within the drive axle group was expected because the drive axle of this configuration consists of a single axle. The single axle drive group equates to larger ESAL increases with smaller weight increases when compared to a standard tandem drive axle. Higher variability within the eastbound trailer axle may have been due to minor roughness prior to the scales and/or the error observed within the eastbound scales during the validation analysis in Chapter 3.

**Table 4.12 - Westbound and Eastbound Class 11 Mean ESALs**

| | GVW ESALs | Steering Axle ESALs | Drive Axle ESALs | Trailer Tandem Axle ESALs |
|---|---|---|---|---|
| **WESTBOUND CURB LANE** | | | | |
| Mean Load | 0.37 | 0.08 | 0.22 | 0.07 |
| 95th Percentile | 2.47 | 0.35 | 1.25 | 0.21 |
| **EASTBOUND CURB LANE** | | | | |
| Mean Load | 0.44 | 0.07 | 0.33 | 0.04 |
| 95th Percentile | 1.76 | 0.36 | 1.58 | 1.76 |

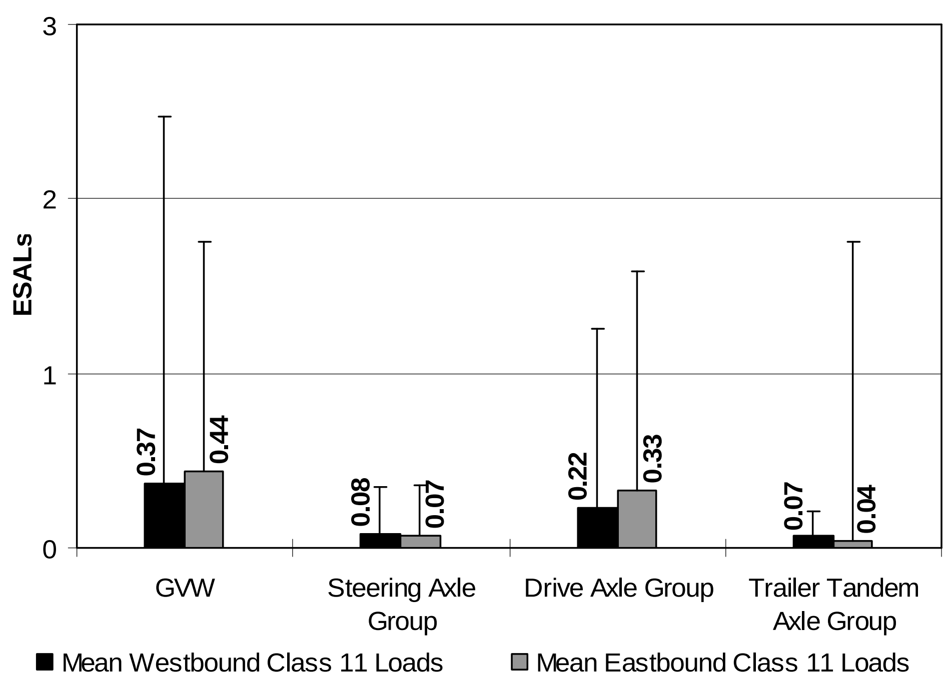


**Figure 4.23 - Westbound and Eastbound Class 11 Mean ESALs (+ 95th Percentile)**

Analysis of the Class 11 cumulative loads by axle group, illustrated in Figure 4.24, indicated that the largest portion of cumulative GVW ESALs was contributed by the drive axle, at 60 and 76 percent in the westbound and eastbound curb lanes. This large contribution was due to the unique Class 11 trailer axle configuration, where a single drive axle is utilized instead of a tandem drive axle, resulting in greater ESALs with small increases in weight.

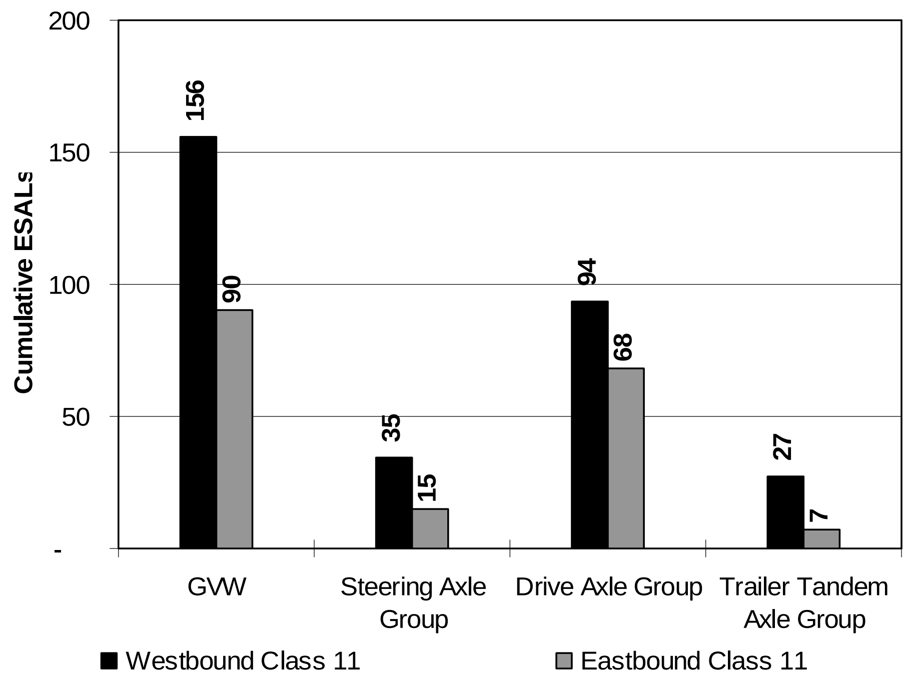


**Figure 4.24 - Westbound and Eastbound Class 11 Cumulative Seven Day ESALs**

### 4.2.5 Class 12 Vehicle Load Analysis

The Class 12 vehicle designation contributed to 27 percent of the population in the seven-day, seven configuration analysis. This configuration represents five axle trucks with tandem drive axle groups and full tandem trailers.

The distribution of westbound and eastbound Class 12 GVW ESALs is illustrated in Figure 4.25. Analysis of the Class 12 GVW ESAL distribution indicated a directional difference in loading and/or commodity due to a tendency for heavier westbound loads. The two major peaks, shown in Figure 4.25, are indicative of vehicle loading trends, where the first peak represents unloaded trips and the second represents trips loaded around legal weight limit. The legal weight limit for Class 12 vehicles on this roadway equated to 3.9 ESALs per vehicle.

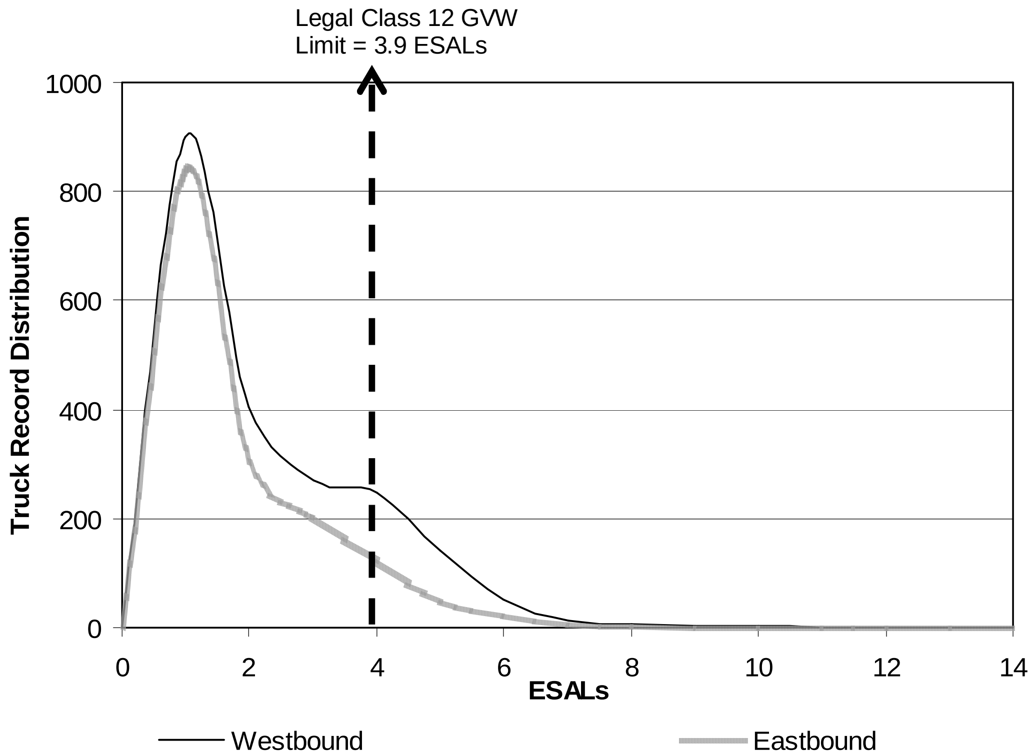


**Figure 4.25 - Distribution of Westbound and Eastbound Class 12 GVW Records**

The Class 12 load distribution is summarized in Table 4.13 and Figure 4.26. The mean directional ESAL distribution indicated that the steering axle groups varied little in comparison to the probability bands for both the drive and trailer axle groups. It was also noted that the drive axle groups had higher mean ESALs than their respective trailer axle groups, which indicated that the load distribution may put more pressure on the drive axle than the trailer axle.

**Table 4.13 - Westbound and Eastbound Class 12 Mean ESALs**

| | GVW ESALs | Steering Axle ESALs | Drive Axle ESALs | Trailer Tandem Axle ESALs |
|---|---|---|---|---|
| **WESTBOUND CURB LANE** | | | | |
| Mean Load | 1.81 | 0.37 | 0.74 | 0.70 |
| 95$^{th}$ Percentile | 4.72 | 0.63 | 2.18 | 2.39 |
| **EASTBOUND CURB LANE** | | | | |
| Mean Load | 1.44 | 0.39 | 0.58 | 0.46 |
| 95$^{th}$ Percentile | 4.05 | 0.70 | 1.80 | 1.84 |

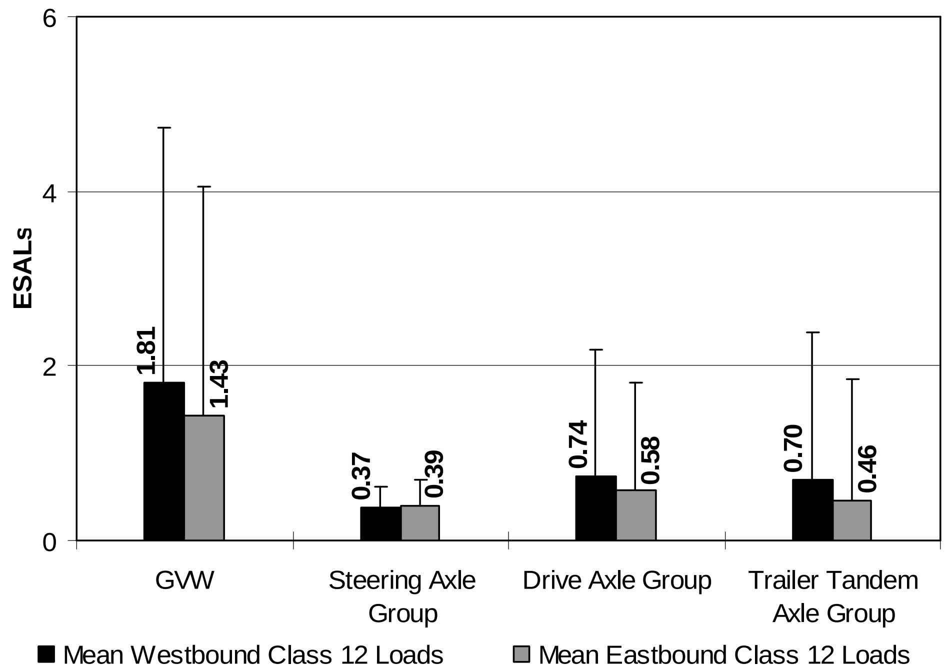


**Figure 4.26 - Westbound and Eastbound Class 12 Mean ESALs (+ 95$^{th}$ Percentile)**

The westbound and eastbound Class 12 steering axle groups contributed nearly one third of the cumulative ESALs for both directions of travel, as illustrated in Figure 4.27. This was most likely due to the single tire configuration of the steering axle group combined with a heavier truck configuration. Since steering axles provide less surface area to distribute load, a more significant impact on the roadway surface can be created with minimal increases in load. However, as noted previously, the drive axle group contributed the largest loads to the cumulative ESAL analyses for both directions, indicating that the distribution of load was typically towards the drive axle group.

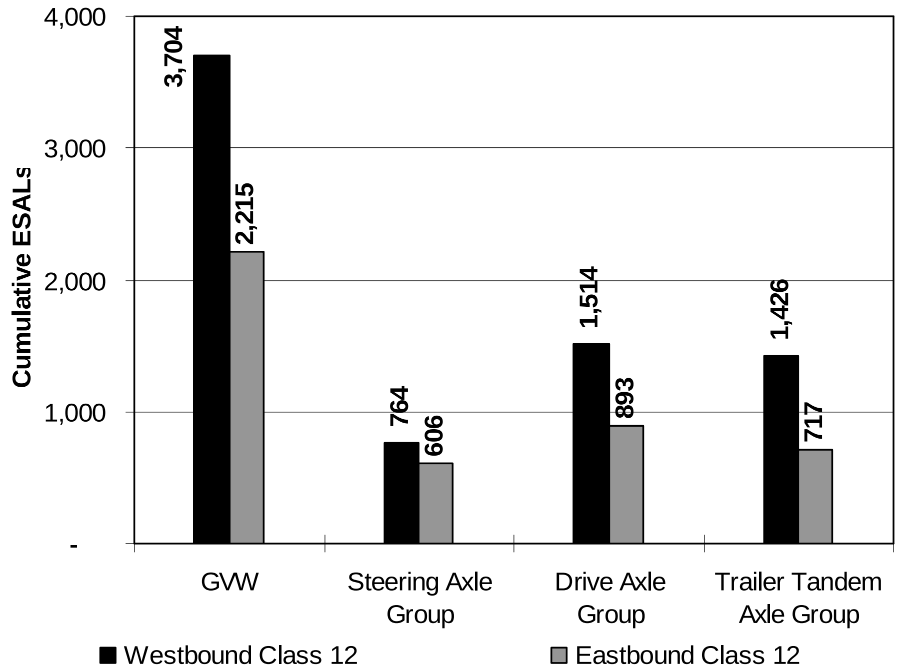


**Figure 4.27 - Westbound and Eastbound Class 12 Cumulative Seven Day ESALs**

### 4.2.6 Class 13 Vehicle Load Analysis

The Class 13 truck designation contributed to 13 percent of the population in the seven day, seven configuration analysis. This configuration represents six axle trucks with tandem drive axle groups and full tridem trailers.

The distribution of Class 13 GVW ESALs is illustrated in Figure 4.28. Analysis of the Class 13 GVW ESAL distribution showed similar loading trends for each direction of travel, but with a more pronounced westbound secondary peak. The secondary peak indicated a tendency for more westbound vehicles to load around the legal weight limit. The legal weight limit for Class 13 vehicles on this roadway equated to 3.8 ESALs per vehicle.

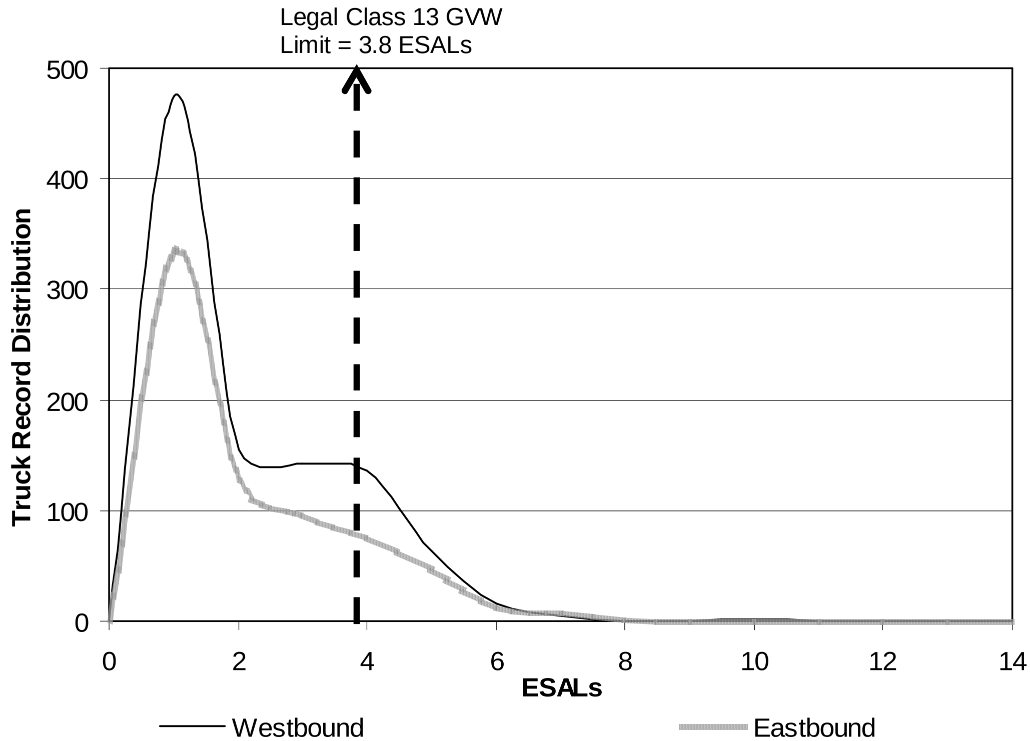


**Figure 4.28 - Distribution of Westbound and Eastbound Class 13 GVW Records**

Class 13 vehicle loads are summarized in Table 4.14 and Figure 4.29. The ESALs generated by the steering axle group were less than one third of the GVW ESALs, and varied little in comparison to the ESAL range of the other axle groups. It was also noted that the drive axle groups exhibited higher mean ESALs than their respective trailer ESALs as compared to the Class 12 vehicle group.

**Table 4.14 - Westbound and Eastbound Class 13 Mean ESALs**

| | GVW ESALs | Steering Axle ESALs | Drive Axle ESALs | Trailer Tridem Axle ESALs |
|---|---|---|---|---|
| **WESTBOUND CURB LANE** | | | | |
| Mean Load | 1.69 | 0.33 | 0.78 | 0.58 |
| $95^{th}$ Percentile | 4.41 | 0.57 | 2.21 | 2.00 |
| **EASTBOUND CURB LANE** | | | | |
| Mean Load | 1.71 | 0.35 | 0.85 | 0.51 |
| $95^{th}$ Percentile | 4.54 | 0.63 | 2.52 | 1.83 |

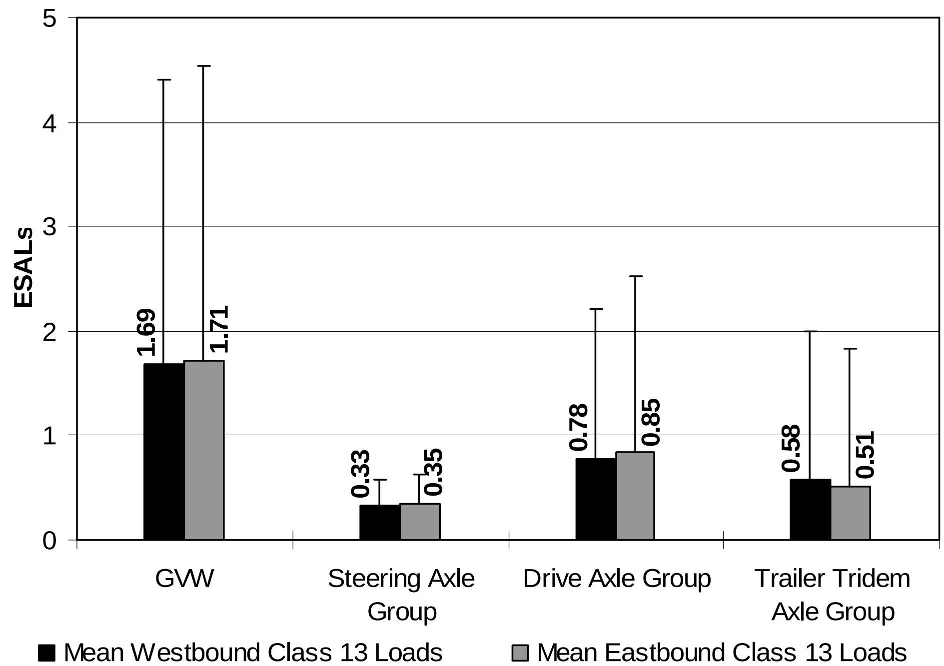


**Figure 4.29 - Westbound and Eastbound Class 13 Mean ESALs (+ 95th Percentile)**

As seen in Figure 4.30, the larger presence of the steering axle group was most likely due to the effects of a heavier vehicle on a single tire axle configuration.

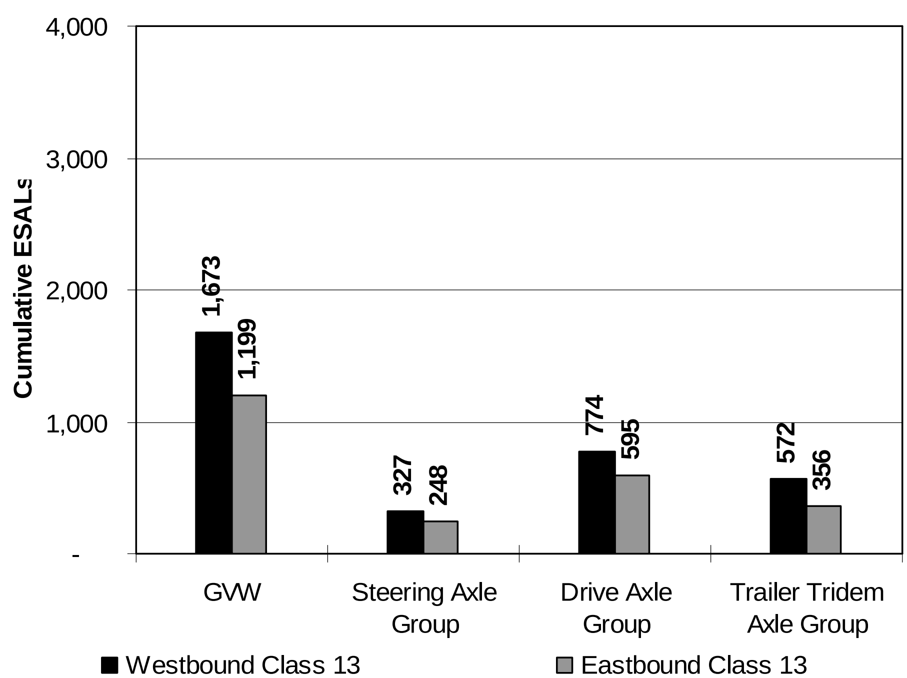


**Figure 4.30 - Class 13 Westbound and Eastbound Cumulative Seven Day ESALs**

### 4.2.7 Class 19 Vehicle Load Analysis

The Class 19 truck configuration contributed to 15 percent of the population in the seven day, seven configuration analysis. This configuration represents eight axle B-trains typically used for resource-based bulk commodity hauling, as illustrated in Figure 4.31.


**Figure 4.31 – Eight Axle B-Train, Federated Co-Operatives Ltd.**

The distribution of westbound and eastbound Class 19 GVW ESALs is illustrated in Figure 4.32. The dual peaks evident in Figure 4.32 indicate the presence of unloaded and loaded vehicles, whereby unloaded vehicles are represented in the first peak from one to two ESALs, and loaded vehicles in the second peak ranging from four to seven ESALs. Analysis of the Class 19 GVW ESAL distribution showed similar loading trends between each direction of travel. The similarity between directional GVW ESAL distributions for this class may have been due to the commodity and operational routing of resource bulk carriers, whereby few trips are completed empty and nearly all trips are subject to rural weight enforcement. The legal weight limit for Class 19 vehicles on this roadway equated to 5.3 ESALs per vehicle.

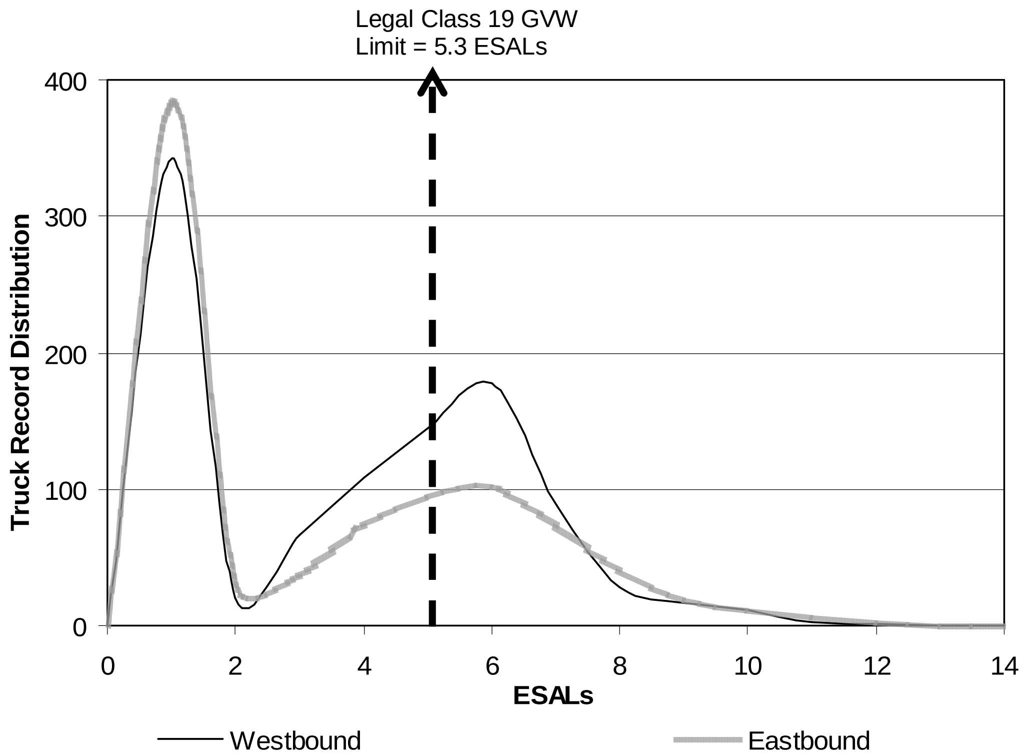


**Figure 4.32 - Distribution of Westbound and Eastbound Class 19 GVW Records**

The distribution of Class 19 ESALs, outlined in Table 4.15 and Figure 4.33, showed loading trends similar to those observed for Classes 4, 12 and 13, where:

- The steering axle group had a minimal effect on the overall GVW ESALs (Class 4 only) and demonstrated little variance between the mean and 95$^{th}$ percentile ESALs;
- The drive axle group contributed most of the GVW ESALs, and;
- The 95$^{th}$ percentile probability bands of the trailer axle groups exhibited similar variances as those observed for the drive axle groups.

**Table 4.15 - Westbound and Eastbound Class 19 Mean ESALs**

| | GVW ESALs | Steering Axle ESALs | Drive Axle ESALs | Trailer Tridem Axle ESALs | Trailer Tandem Axle ESALs |
|---|---|---|---|---|---|
| **WESTBOUND CURB LANE** | | | | | |
| Mean Load | 3.38 | 0.35 | 1.13 | 0.80 | 1.10 |
| $95^{th}$ Percentile | 7.36 | 0.56 | 2.52 | 2.52 | 2.84 |
| **EASTBOUND CURB LANE** | | | | | |
| Mean Load | 3.12 | 0.44 | 1.11 | 0.79 | 0.79 |
| $95^{th}$ Percentile | 7.84 | 0.72 | 2.89 | 2.19 | 2.46 |

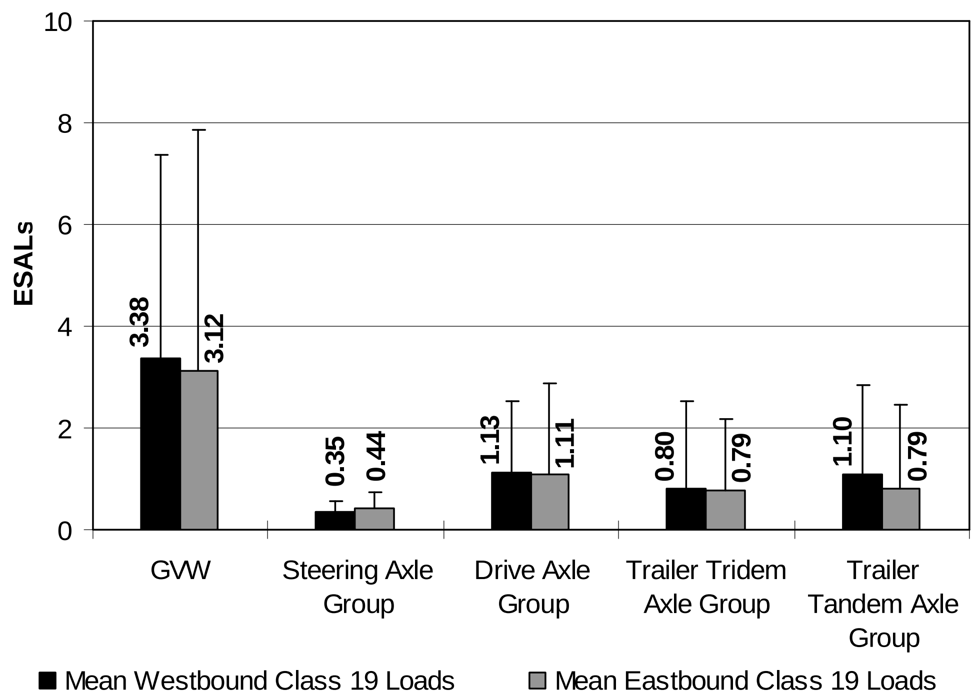


**Figure 4.33 - Westbound and Eastbound Class 19 Mean ESALs (+ $95^{th}$ Percentile)**

As illustrated in Figure 4.34, the steering axle group contribution to the cumulative GVW ESALs in either direction was small in comparison to the ESALs contributed by the other axle groups. The steering axle group contributed 10 and 14 percent of the total GVW ESALs for the westbound and eastbound directions of travel. The drive axle group contributed most of the cumulative GVW ESALs, at 33 and 35 percent for the westbound and eastbound curb lanes. The trailer tridem and tandem axle groups contributed 24 and 33 percent of the westbound GVW cumulative ESALs, and 25 percent each of the eastbound GVW cumulative ESALs.

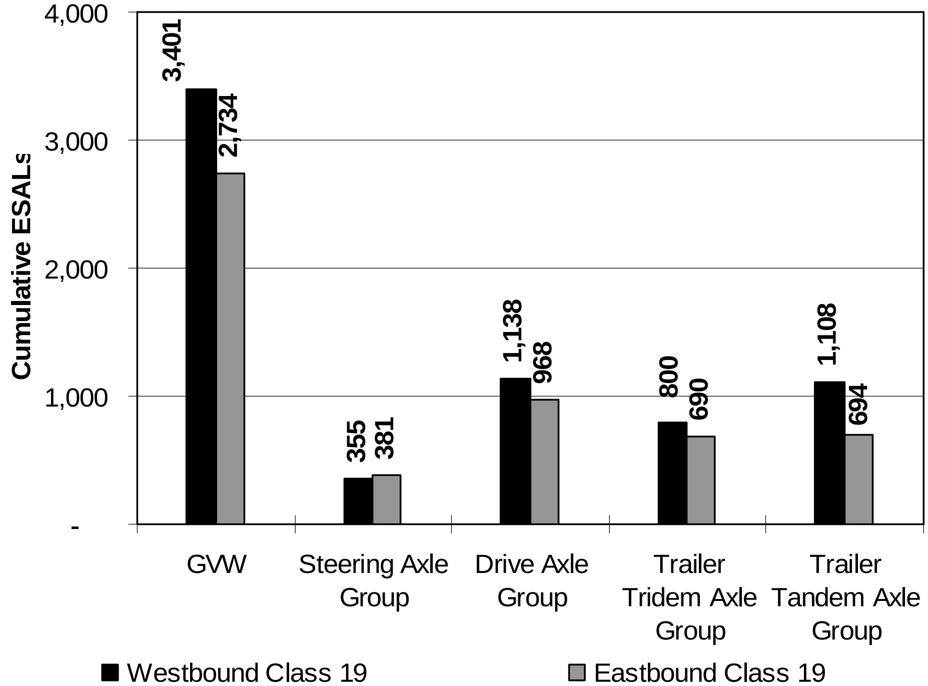


**Figure 4.34 - Class 19 Westbound and Eastbound Cumulative Seven Day ESALs**

## 4.3 Overweight Analysis

The presence of Class 19 vehicles in the cumulative ESAL assessment was larger than would be expected based on their contribution to the study population and vehicle dimensions. This indicated that overloading could be occurring more frequently within this vehicle group than others.

As summarized in Table 4.16 and Figure 4.35, approximately one quarter of the Class 19 vehicle records were over the maximum GVW limits specified by the SDHT. Class 19 vehicles had more overweight records than any other configuration, with the exception of eastbound Class 6 vehicles. The high occurrence of overweight Class 19 records may have been due to an agreement between the SDHT and provincial trucking establishments allowing some trucks to load over legal limits pending specific operating and commodity requirements. The large presence of overweight eastbound Class 6 records was due to a directional difference between loaded and unloaded trips, where loads typically exceeded legal weight limits.

**Table 4.16 – Vehicle Records Exceeding Legal Weight Limits**

| Overweight Records | Class 4 | Class 5 | Class 6 | Class 11 | Class 12 | Class 13 | Class 19 |
|---|---|---|---|---|---|---|---|
| **WESTBOUND CURB LANE** | | | | | | | |
| GVW | 7% | 10% | 3% | 2% | 13% | 10% | 27% |
| Steering Axle | 0% | 12% | 4% | 4% | 39% | 26% | 32% |
| Drive Axle | 13% | 10% | 3% | 4% | 11% | 15% | 32% |
| Trailer Tridem | - | - | - | - | - | 9% | 20% |
| Trailer Tandem | - | - | - | 1% | 13% | - | 28% |
| **EASTBOUND CURB LANE** | | | | | | | |
| GVW | 8% | 8% | 28% | 2% | 6% | 11% | 26% |
| Steering Axle | 2% | 11% | 45% | 4% | 44% | 31% | 57% |
| Drive Axle | 15% | 12% | 16% | 6% | 6% | 17% | 33% |
| Trailer Tridem | - | - | - | - | - | 8% | 27% |
| Trailer Tandem | - | - | - | 0% | 6% | - | 18% |

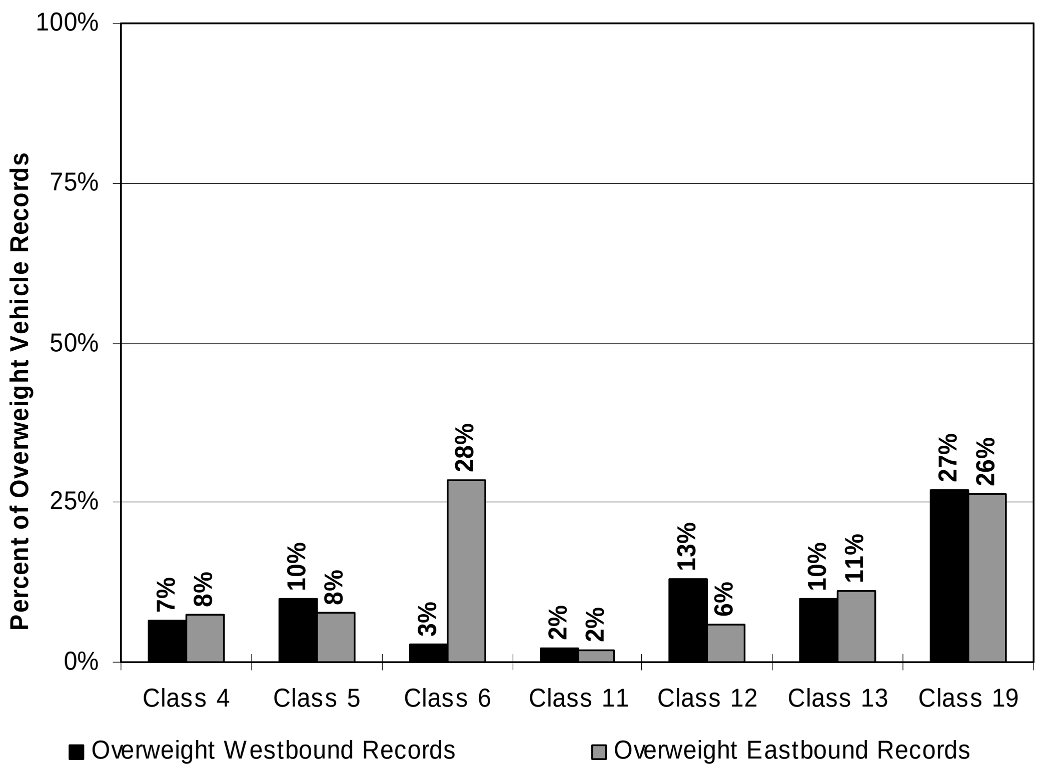


**Figure 4.35 – Westbound and Eastbound Overweight GVW Records by Class**

Comparison of Figures 4.36 and 4.37 identified a large number of overweight records in the eastbound curb lane due primarily to a high number of overweight Class 6 vehicles. As seen in Figure 4.37, 28 percent of the eastbound Class 6 GVW ESALs and 45 percent of eastbound Class 6 steering axle loads were over legal weight limits. In contrast, Figure 4.36 indicates that only 3 percent of the westbound Class 6 GVW records, 4 percent of the westbound Class 4 steering loads and 3 percent of the westbound Class 6 drive axle loads were overweight.

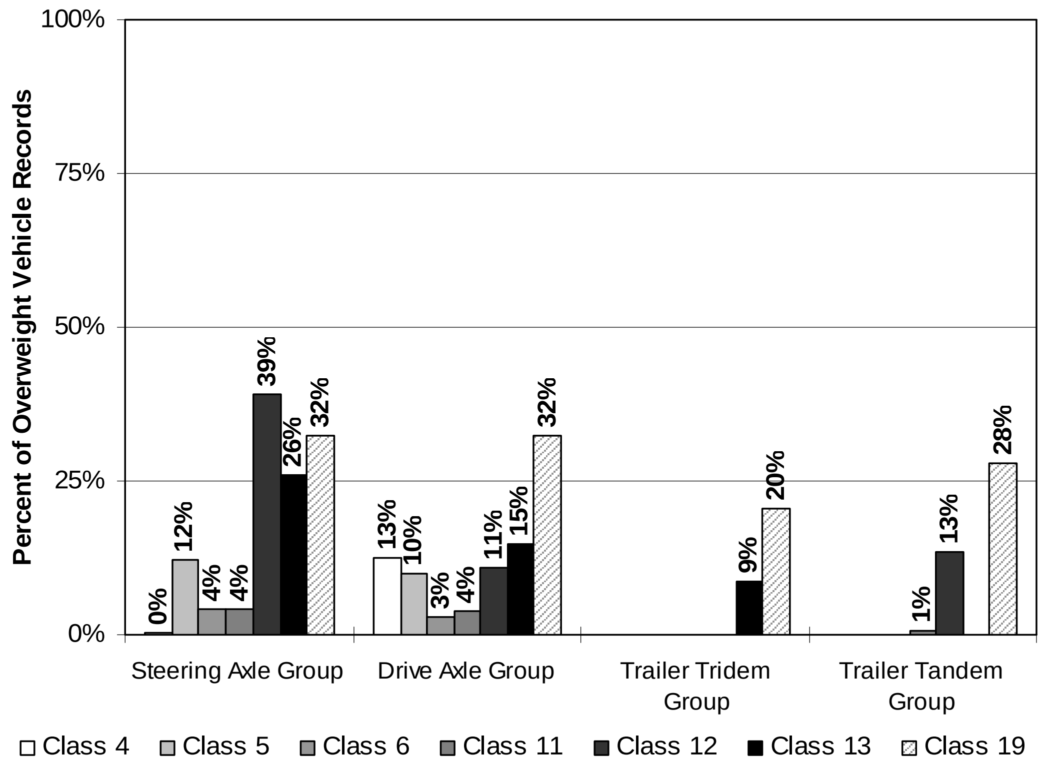


**Figure 4.36 – Percent of Overweight Westbound Vehicle Records by Class**

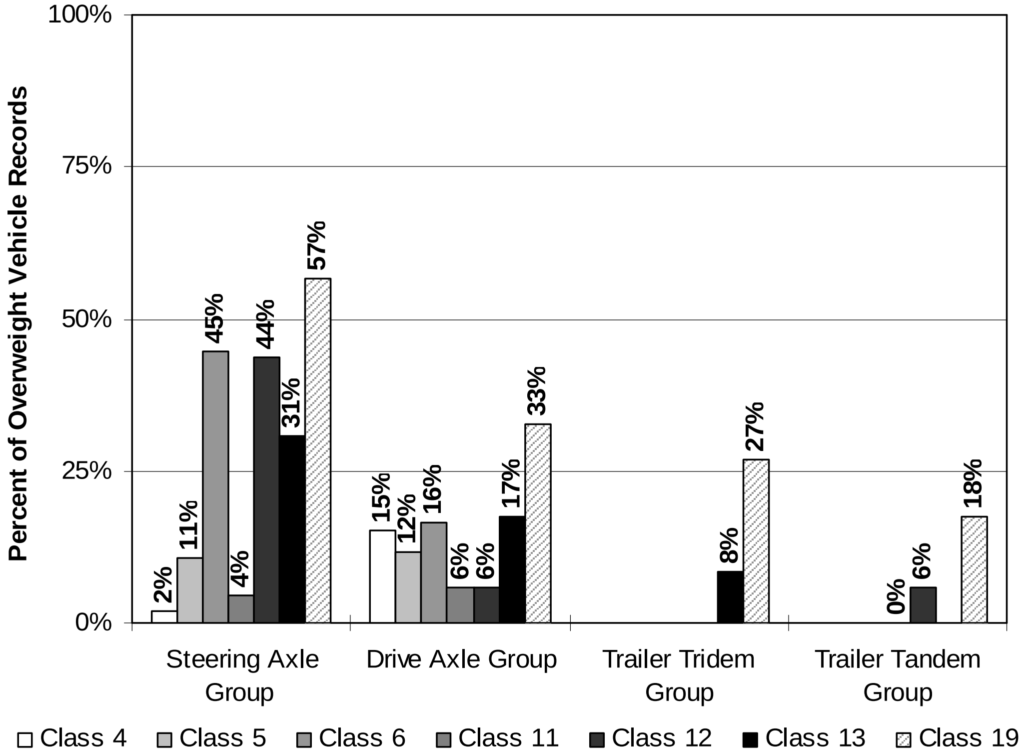


**Figure 4.37 – Percent of Overweight Eastbound Vehicle Records by Class**

Complete results of the overweight ESAL assessment are provided in Appendix F. A comparison of the seven day cumulative overweight GVW ESALs observed in both directions of travel is summarized in Table 4.17 and Figure 4.38. Of the 11,420 ESALs recorded in the westbound curb lane, 1,070 ESALs (nine percent of the westbound ESALs) were caused by loads that were above legal weight limits. Similarly, nine percent (802 ESALs) of the 8,860 cumulative eastbound curb lane ESALs were caused by loads that above legal weight limits.

**Table 4.17 – Seven Day Cumulative Overweight ESALs by Lane and Vehicle Configuration**

| ESALs Over Legal Limit | Steering Axle Group | Drive Axle Group | Trailer Tridem Axle Group | Trailer Tandem Axle Group | GVW |
|---|---|---|---|---|---|
| **WESTBOUND CURB LANE** | | | | | |
| Class 4 | 6 | 190 | - | - | 111 |
| Class 5 | 193 | 124 | - | - | 226 |
| Class 6 | 30 | 32 | - | - | 53 |
| Class 11 | 11 | 19 | - | 3 | 9 |
| Class 12 | 95 | 132 | - | 201 | 263 |
| Class 13 | 29 | 74 | 51 | - | 83 |
| Class 19 | 29 | 141 | 77 | 196 | 325 |
| TOTAL | 393 | 712 | 127 | 400 | 1,070 |
| **EASTBOUND CURB LANE** | | | | | |
| Class 4 | 39 | 199 | - | - | 124 |
| Class 5 | 92 | 87 | - | - | 89 |
| Class 6 | 30 | 15 | - | - | 39 |
| Class 11 | 1 | 18 | - | 0 | 8 |
| Class 12 | 97 | 43 | - | 70 | 95 |
| Class 13 | 31 | 85 | 25 | - | 80 |
| Class 19 | 71 | 190 | 116 | 96 | 367 |
| TOTAL | 362 | 637 | 141 | 166 | 802 |

As shown in Figure 4.38, most of the overweight ESALs were contributed by:

- Westbound and eastbound Class 19 vehicles, which contributed 30 and 46 percent of the total overweight ESALs for either direction of travel;
- Westbound Class 12 vehicles, which contributed approximately one quarter of the overweight ESALs in the westbound curb lane, and;
- Westbound Class 5 vehicles, which contributed 21 percent of the overweight ESALs in the westbound direction of travel.

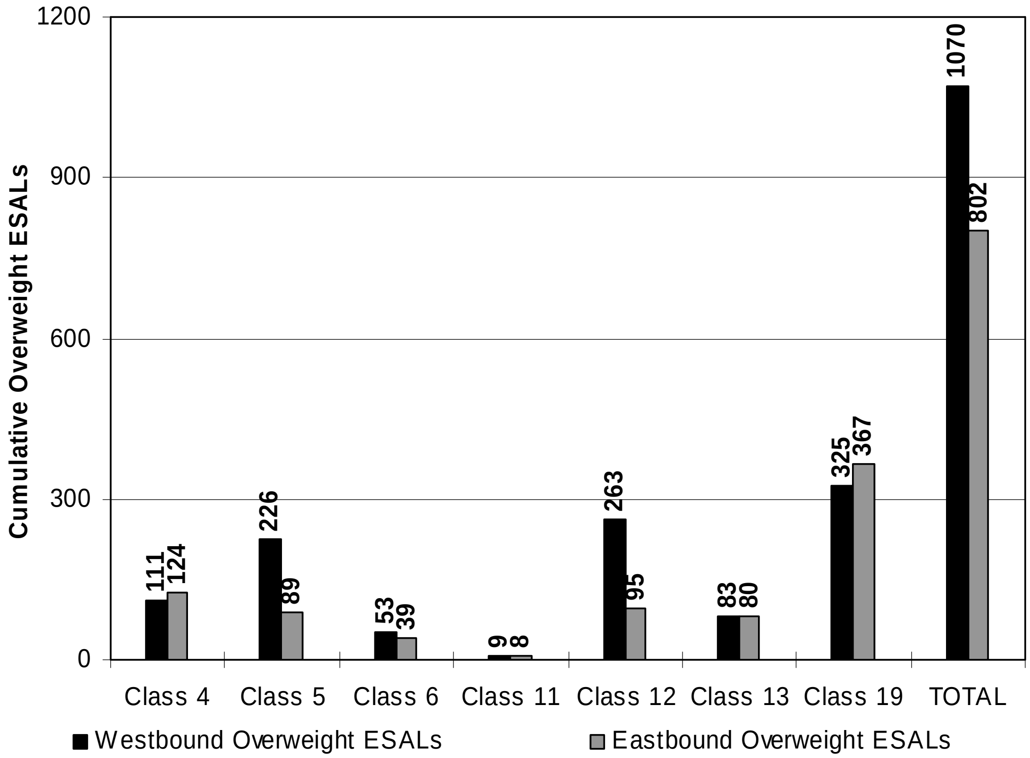


**Figure 4.38 - Seven Day Cumulative Overweight ESALs by Lane and Vehicle Configuration**

As summarized in Figure 4.39, nearly three quarters of the cumulative westbound curb lane overweight ESALs were contributed by Class 4 drive axle groups, Class 5 steering axle groups, and Class 12 and 19 trailer tandem axle groups. Similarly, 87 percent of the cumulative eastbound curb lane overweight ESALs, shown in Figure 4.40, were contributed by Class 4 and 19 drive axle groups, Class 12 steering axle groups, and Class 19 trailer axle groups.

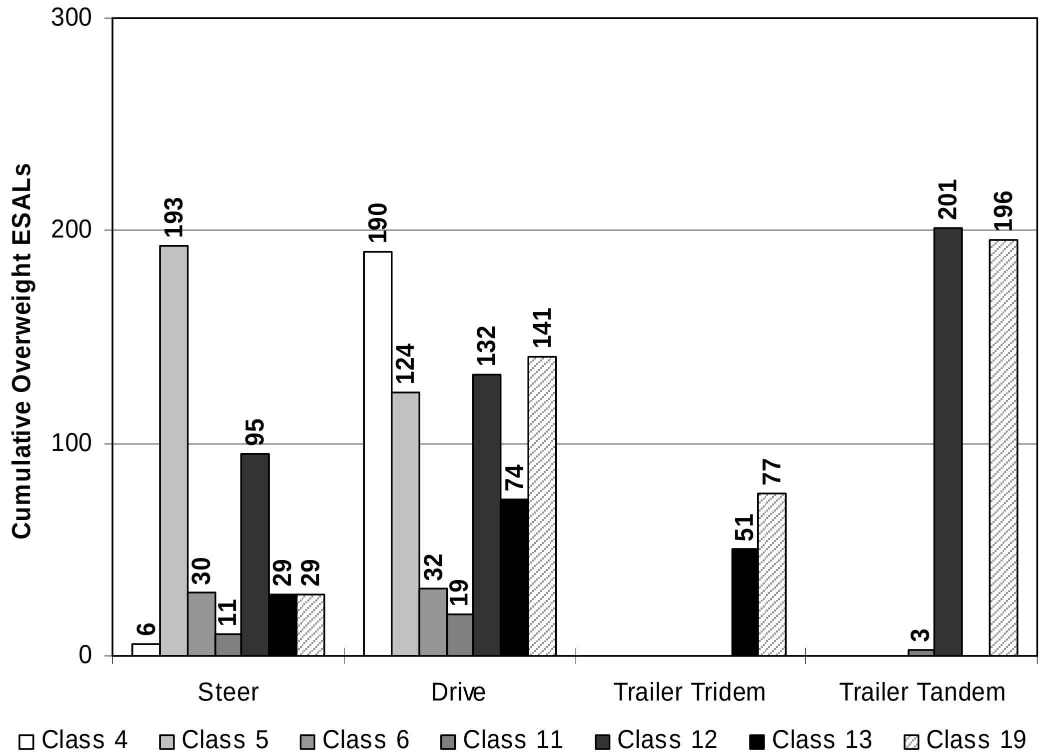


**Figure 4.39 - Westbound Overweight ESALs by Axle Group**

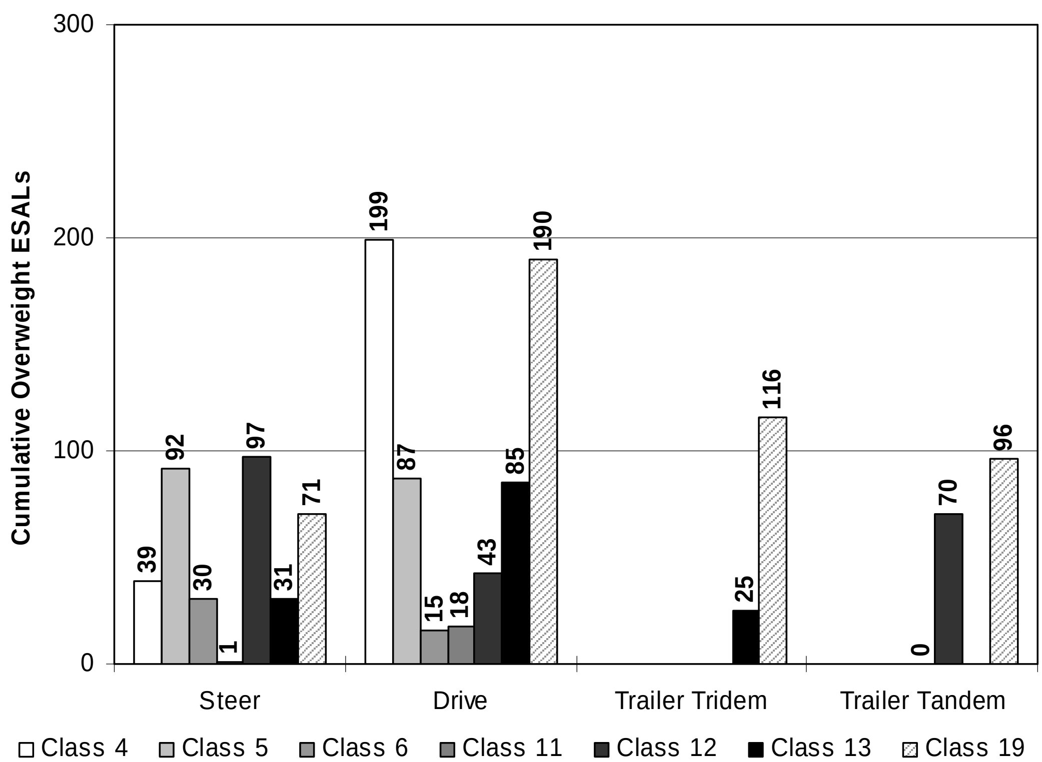


**Figure 4.40 –Eastbound Overweight ESALs by Axle Group**

### 4.4 Commercial Vehicle Load Spectra in Saskatoon Summary

This chapter generated a freeway commercial vehicle load spectra for the assessment of commercial vehicle loading on different types of urban roadways in Saskatoon. The freeway commercial vehicle load spectra were generated using data from the Circle/Preston VWIM system over the seven day period from May 12, 2006 until May 18, 2006. Truck data was collected and classified based on a twenty category classification system of truck configurations utilized by the Saskatchewan Department of Highways and Transportation.

Analysis of the seven days of data indicated that 97 percent of the commercial traffic stream consisted of: Class 4 (two axle straight truck); Class 5 (three axle straight truck); Class 6 (straight truck with tandem steering); Class 11 (four axle tractor-semi unit); Class 12 (five axle tractor-semi unit); Class 13 (six axle tractor-semi unit), and; Class 19 configurations (eight axle tractor-semi combination units). A total of 16,525 truck records were obtained from the seven configurations during the study. A 50/50 directional traffic split was observed between the westbound and eastbound lanes, and 77 percent of the vehicles were observed traveling in the westbound and eastbound curb lanes. As such, only the curb lanes were assessed further to determine the CVO trends that would establish the spectra.

Percentile and cumulative distributions of GVW and axle group ESALs indicated that:

- Differences in loading trends due to directionality could be expected with nearly all configurations, particularly in Class 6 (generally mobile concrete mixers), but with the exception of Class 19 vehicles;
- Class 5 and 6 typically had steering axle loads that were larger in proportion to their GVW than the other classes. This may have represented varying uniformity among commodity types (Class 5), shifted load carrying capacity (Class 6) and/or the effects of minor load increases as transmitted through smaller axle groups;

- Class 11 generally had the smallest range between its mean and 95$^{th}$ percentile GVW, which indicated potential uniformity amongst commodity types, and;
- Class 19 and eastbound Class 6 had the largest range between their mean and 95$^{th}$ percentile GVW, which indicated a decrease in uniformity within the loads (Class 6) and/or range exaggeration due to larger vehicle dimensions (Class 19).

Analysis of the cumulative loads indicated that both Class 19 and 12 vehicles contributed the majority of the recorded GVW ESALs, at 30 and 29 percent. This was followed by Class 5 and 13 vehicles, with each contributing 14 percent of the cumulative ESALs. With the exception of the Class 19 configuration, these results correlated with the vehicle masses and contribution to the observed population. Furthermore, with the exception of Class 4 vehicles, the westbound curb lane carried more of the vehicle population than the other lanes.

Overloading trends indicated that Class 19 vehicles presented more overweight records than any of the other classes, followed by Class 6, Class 13 and Class 12 vehicles. It was also observed that 9 percent of the cumulative GVW ESALs in either direction of travel were contributed by vehicle loads over legal GVW limits. The overweight ESAL analysis concluded that most of the overweight westbound curb lane ESALs were contributed by Class 4 drive axle groups, Class 5 steering axle groups, and Classes 12 and 19 trailer tandem axle groups. Most of the overweight eastbound curb lane ESALs were contributed by Classes 4 and 19 drive axle groups, Class 12 steering axle groups, and both the Class 19 trailer tridem and tandem axle groups.

# CHAPTER 5 - MECHANISTIC-EMPIRICAL ESALS FOR URBAN ROADWAYS

Recent research has shown that typical road materials can be highly sensitive to shear stress and rate of loading (Berthelot et al. 1999). This is critical in terms of asphaltic pavement performance in that observed urban traffic patterns tend to operate under reduced speeds, frequent stop-and-go conditions, and high density traffic corridors. Consequently, the damage inflicted by commercial vehicles, both overloaded and of legal weight, can be much more drastic in an urban environment than in a rural environment (Berthelot et al. 1999).

ESALs have been the standard traffic loading measure used in highway engineering and pavement management practices for decades. However, there are several limitations to the application of conventional ESALs for use in the engineering and management of urban roadways subjected to modern traffic loads. In addition, AASHTO load equivalencies tend to be low when compared to the actual pavement damages inflicted by repeated truck loads in modern urban conditions. Given the increase in truck traffic as observed over recent years, mechanistic-empirical ESALs may be much higher than conventional AASHTO ESALs.

In 2006, the City of Saskatoon completed a comprehensive roadway structural assessment across City streets. Ground Penetrating Radar (GPR), shown in Figure 5.1, and Heavy Weight Falling Deflectometer (HWD), shown in Figure 5.2, were utilized to assess the structural composition and primary responses of pavements submitted to heavy truck loadings (PSI 2007). GPR was utilized to evaluate surface deterioration and dielectric permittivity profiles, and HWD was utilized to assess non-linear elastic pavement responses, including strain-hardening and weakening behaviours (PSI 2007). Several measures of roadway deflection and primary pavement responses were obtained for a range of weights based on secondary and primary legal weight limits. Various urban road types were tested, including freeways, expressways, arterials, collectors, locals and local-industrial roadways.

**Figure 5.1 – Ground Penetrating Radar, PSI Inc.**

**Figure 5.2 – Heavy Weight Deflectometer, PSI Inc.**

This research attempted to formulate load equivalencies based on the primary weight structural responses obtained in the 2006 City of Saskatoon roadway asset management study.

Since roadway damage can be related to pavement deflection and deformation from applied loads (AASHTO 1993), ratios of primary response data from various urban road types were applied to the freeway ESAL spectra to generate urban load equivalency factors.

### 5.1 Peak Deflection-Based Urban ESALs

A range of loads based on secondary and primary weight limits were applied to various road classes throughout the City of Saskatoon using HWD to measure roadway deflections. The roadway structural responses are summarized in Table 5.1. Photos of segments of the test locations are included in Appendix G.

A continuous segment of Circle Drive, from the west abutment of the Circle Drive Bridge to Avenue C, was utilized to represent the typical primary weight loading responses of urban freeway and expressway flexible pavements. Circle Drive eastbound from Faithfull Avenue to Avenue C was omitted from this analysis because it consisted of jointed plain concrete pavement and was not representative of the loading responses of flexible pavement.

The peak measured surface deflections obtained in the City of Saskatoon study were typically greatest closer to the Circle Drive Bridge, averaging 0.95 mm and 0.65 mm for the eastbound and westbound directions. The average deflection across all lanes in both directions of travel on Circle Drive was 0.46 mm with a standard deviation of 0.10, as presented in Table 5.2 and Figure 5.3.

Table 5.1 - Urban Roadway Deflections under Primary Loading

| Road Name | Location | Primary Loading Deflection (mm) | | | |
|---|---|---|---|---|---|
| | | EB/SB CL | EB/SB ML | WB/NB ML | WB/NB CL |
| **FREEWAY/EXPRESSWAY ROADS** | | | | | |
| Circle Drive | W Bridge Abutment to Median Gore | 0.49 | 0.46 | 0.62 | 0.67 |
| | Median Gore Point to Millar Ave | 0.49 | 0.44 | 0.55 | 0.67 |
| | Millar Ave to 1st Ave N | 0.39 | 0.435 | 0.33 | 0.36 |
| | 1st Ave N to Faithfull Ave | 0.51 | 0.38 | 0.455 | 0.43 |
| | Faithfull Ave to E Bridge Abutment | - | - | 0.425 | 0.43 |
| | E Bridge Abutment to Ave C | - | - | 0.295 | 0.39 |
| | Average | 0.47 | 0.43 | 0.45 | 0.49 |
| **ARTERIAL ROADS** | | | | | |
| 8th Street | Boychuk Dr to McKercher Dr | 0.86 | 0.8 | 0.85 | 1.02 |
| Attridge Dr | McOrmond Dr to Kenderdine Rd | 0.79 | 0.77 | 0.76 | 0.82 |
| | Kenderdine Rd to Berini Dr | 0.96 | 0.95 | 0.9 | 1.13 |
| | Berini Dr to Central Ave | 0.76 | 0.74 | 0.74 | 0.77 |
| Ave C | Circle Dr to 47th St | 0.85 | 0.62 | 0.6 | 0.81 |
| Preston Ave | 8th St to Main St | 0.7 | - | - | 0.6 |
| | Main St to 14th St | 0.88 | - | - | 0.79 |
| | Average | 0.83 | 0.78 | 0.77 | 0.85 |
| **COLLECTOR & LOCAL ROADS** | | | | | |
| Kenderdine Rd | 115th St to Attridge Dr | 1.76 | - | - | 2.16 |
| 31st St | Ave R to Ave W | 0.83 | - | - | 0.83 |
| Adelaide St | McKinnon Ave to Haultain Ave | 1.46 | - | - | 1.46 |
| Rylston Rd | Witney Ave to Ave X | 1.09 | - | - | 1.09 |
| | Average | 1.29 | - | - | 1.39 |
| **LOCAL-INDUSTRIAL ROADS** | | | | | |
| Idylwyld Service Rd | 60th St to 71st St | 0.67 | - | - | 0.67 |
| Edson St | Jasper Ave to Portage Ave | 0.50 | - | - | 0.50 |
| Jasper Ave | Melville St to Edson St | 0.57 | - | - | 0.57 |
| Portage Ave | Melville St to Edson St | 0.65 | - | - | 0.65 |
| | Average | 0.60 | | | 0.60 |

**Table 5.2 - Urban Roadway Primary Loading Deflection Analysis by Road Type**

| Road Type | Mean Peak Surface Deflection (mm) | St. Dev. | CV |
|---|---|---|---|
| Freeway/Expressway | 0.46 | 0.10 | 22% |
| Arterial | 0.81 | 0.13 | 15% |
| Local-Industrial | 0.6 | 0.07 | 12% |
| Local & Collector | 1.34 | 0.47 | 35% |

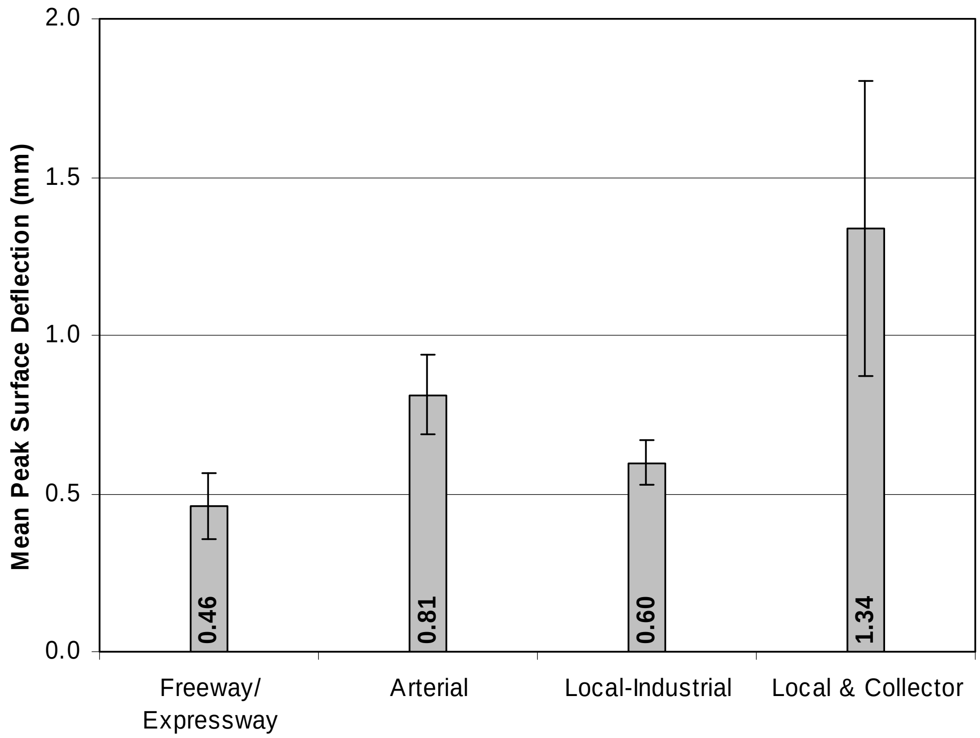


**Figure 5.3 - Mean Deflection by Road Type (± 2 St. Dev.)**

The arterial roadway deflections ranged from 0.60 mm to 1.13mm and the highest deflections were typically located in the curb lanes, as presented in Table 5.1. The mean arterial deflection and standard deviation were 0.81 mm and 0.13, as summarized in Table 5.2 and Figure 5.3.

Only one collector roadway was tested and resulted in high deflections of 1.76 mm to 2.16 mm due to the relatively poor structural condition of the roadway (City of Saskatoon 2007). Three local roadways were tested, resulting in deflections ranging from 0.83 mm to 1.46 mm.

Since the collector roadway exhibited similar deflections to those observed on the local roadways, their deflections were combined to create a new category of roadway (Local & Collector) with a mean deflection of 1.34 mm and a standard deviation of 0.47.

The peak surface deflection of the local-industrial roadways ranged from 0.50 mm to 0.67 mm with an average deflection of 0.60 mm and a standard deviation of 0.07. The local-industrial roadways tested for the 2006 structural assessment were located within industrial areas comprising of a large truck population. The tested roadways had recently been upgraded or previously maintained in such a manner as to facilitate the movement of large trucks, thereby generating lower than normal primary response deflections that were only slightly larger than those obtained on Circle Drive. It is postulated that the majority of the local-industrial roadways within the City of Saskatoon would most likely produce deflections ranging between those obtained on Circle Drive and those recorded for major arterials within City limits.

Pavements may be structurally distressed through deformations, such as deflection, or load-associated fracture (AASHTO 1993). As such, primary deflections measured on various roadways throughout the City were compared with the primary deflection of a section of expressway near the Circle/Preston VWIM site to establish a structural comparison. Comparison ratios were calculated as outlined in Equation 5.1 and allowed for an assessment of the load-bearing capacity of different types of urban roadways with the urban freeway/expressway as a general base line. The potential range of deflection ratios was assessed by calculating the ratio of the range in structural deflection for arterials, collectors, locals and local-industrial roadways over the mean expressway baseline deflection, as outlined in Equation 5.2.

$$\textit{Deflection ratio} = \frac{\delta_i}{\delta_{Freeway\,/\,Expressway}} \qquad [5.1]$$

Where:

$\delta_i$ = the mean peak surface deflection (mm) under primary loads for test road class *i*;

$\delta_{Freeway/Expressway}$ = the mean peak surface deflection (mm) under primary loads for the freeways/expressways.

$$\textit{Deflection ratio range} = \frac{\delta_i \pm 2\sigma_i}{\delta_{Freeway\,/\,Expressway}} \qquad [5.2]$$

Where:

$\delta_i$ = the mean peak surface deflection (mm) under primary loads for test road class i;

$\sigma_i$ = the standard deviation of the peak surface deflections (mm) under primary loads for road class i;

$\delta_{Freeway/Expressway}$ = the mean peak surface deflection (mm) under primary loadings for the freeways/expressways.

ESALs are a measure of the roadway load response for a primary rural highway (AASHTO 1993). In an urban context, freeway and expressway pavement structures are typically comparable to a primary rural highway pavement structure. Therefore, the deflection ratio offered an estimate of the probable loading response attainable on various urban road types using freeway/expressway deflections as a baseline. The resulting urban roadway deflection ratios are summarized in Table 5.3 and Figure 5.4.

As presented in Table 5.3 and Figure 5.4, the mean deflection ratios of each urban road class increased as road classification moved from arterial to local. This was indicative of greater pavement deflection under primary loads and correlated to a thinning of the overall pavement structure as testing shifted from freeways/expressways to local road types. The range in deflection, represented by the mean deflection ratio ± two standard deviations, was greater for the local and collector road types than for the other urban road types. This indicated that more structural variation was present within the lower classes of urban roadway than the higher road classes.

**Table 5.3 - Roadway Deflection Ratios**

| Roadway | Mean Deflection Ratio | Mean Deflection Ratio - 2 St. Dev. | Mean Deflection Ratio + 2 St. Dev. |
|---|---|---|---|
| Freeway/Expressway | 1.0 | - | - |
| Arterial | 1.8 | 1.2 | 2.3 |
| Local-Industrial | 1.3 | 1.0 | 1.6 |
| Local & Collector | 2.9 | 0.9 | 5.0 |

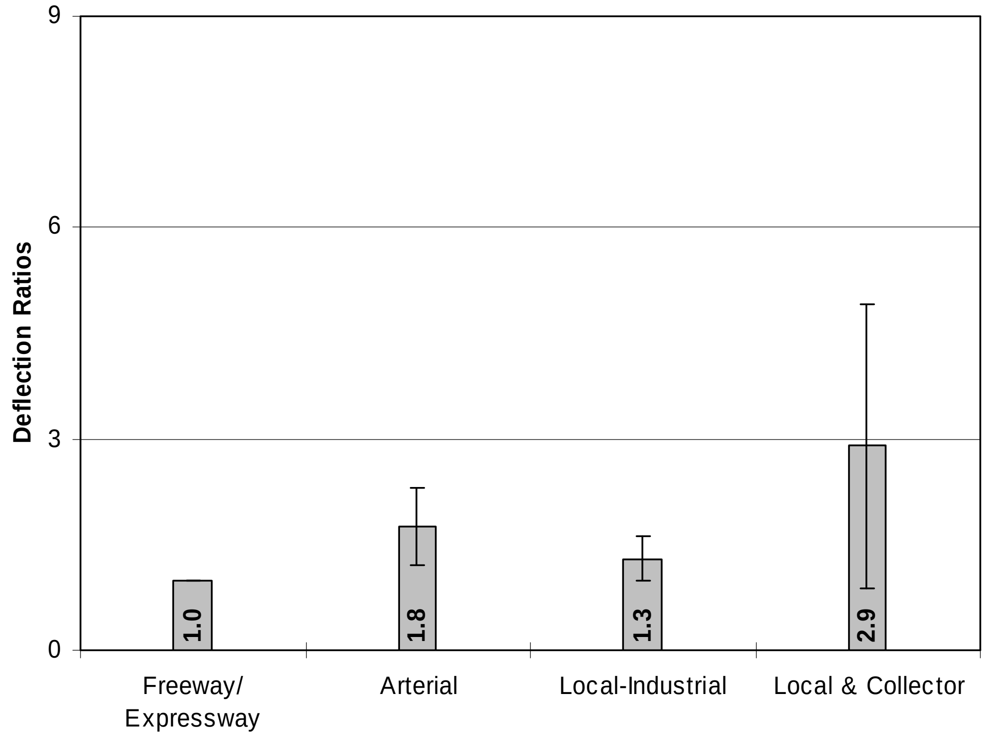


**Figure 5.4 – Peak Primary Surface Deflection Ratios by Urban Road Class (± 2 St. Dev.)**

Combining structural deflection ratios with mean GVW ESALs from the load spectra developed in Chapter 4 provided a simple method of estimating the potential range of urban loading responses to different vehicle configurations. Table 5.4 and Figure 5.5 summarize the results of the deflection ratios combined with the GVW ESALs. As seen in Table 5.4 and Figure 5.5, the mean GVW ESALs increased as the urban road classification shifted from freeway/expressway to local. Based on the mean and the range of deflection ratios, the local and collector roadways displayed the largest increase in mean and range of ESALs as compared to the freeway and expressway baseline ESALs.

**Table 5.4 – Deflection Ratio Mean GVW ESALs by Road Class**

| Mean GVW ESALs | Freeway/ Expressway | Arterial | Local-Industrial | Local & Collector |
|---|---|---|---|---|
| Class 4 | 0.9 | 1.6 | 1.2 | 2.6 |
| Class 5 | 1.2 | 2.1 | 1.5 | 3.4 |
| Class 6 | 1.4 | 2.5 | 1.8 | 4.1 |
| Class 11 | 0.4 | 0.7 | 0.5 | 1.2 |
| Class 12 | 1.6 | 2.9 | 2.1 | 4.7 |
| Class 13 | 1.7 | 3.0 | 2.2 | 4.9 |
| Class 19 | 3.3 | 5.7 | 4.2 | 9.4 |

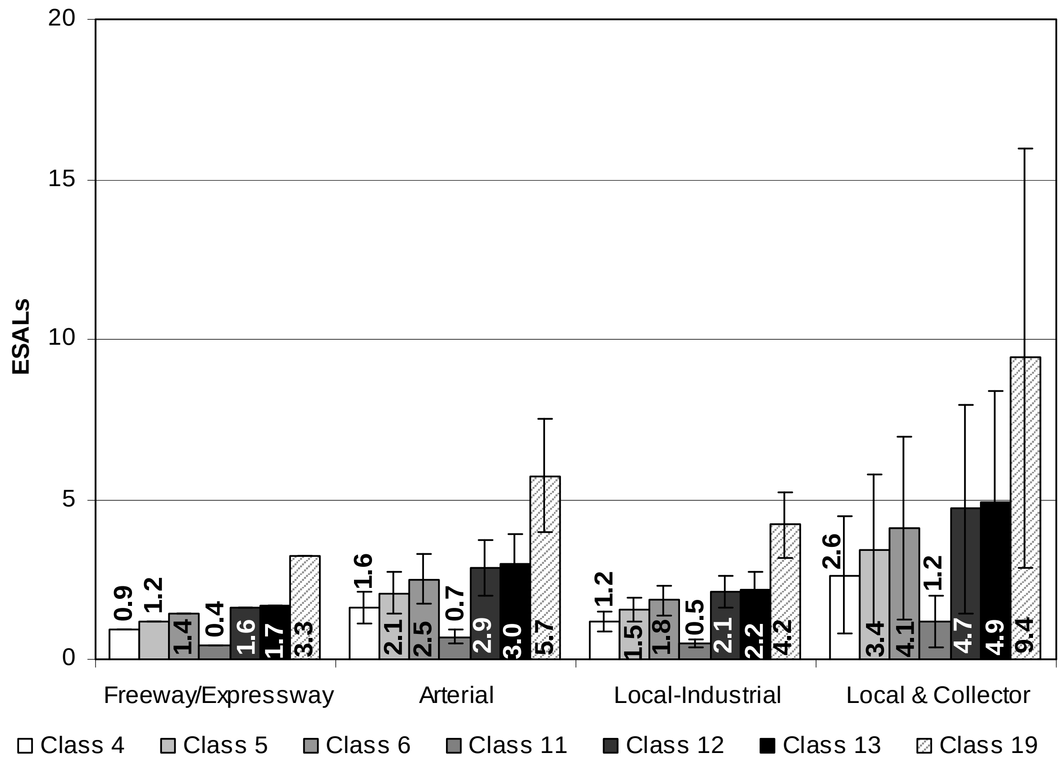


**Figure 5.5 - Mean GVW ESALs per Deflection Ratio (± 2 St. Dev. Deflection Ratio)**

Local and collector roadways exhibited the largest percent increase in ESALs compared to the baseline freeway/expressway ESALs, as presented in Table 5.5 and Figure 5.6. Local-industrial roadways exhibited the smallest percent increase and smallest range in ESALs compared to the baseline freeway/expressway ESALs.

**Table 5.5 - Percent Difference in Deflection Ratio Load Response by Urban Road Class**

| Roadway | Mean Deflection Ratio | Mean – 2 St. Dev. Deflection Ratio | Mean + 2 St. Dev. Deflection Ratio |
|---|---|---|---|
| Arterial | 76% | 21% | 130% |
| Local-Industrial | 30% | -2% | 61% |
| Local & Collector | 190% | -13% | 392% |

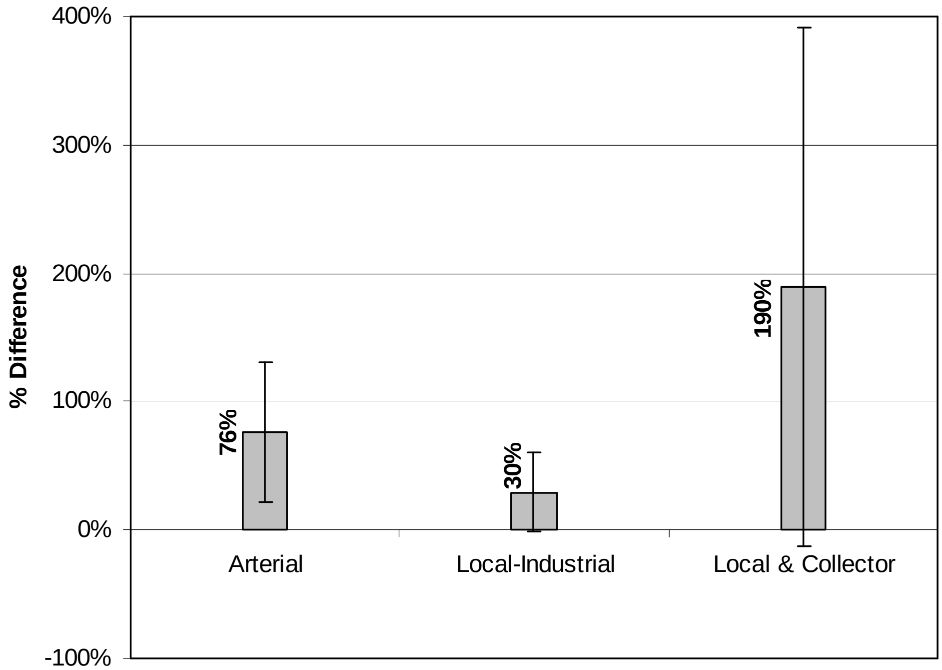


**Figure 5.6 – Deflection Ratio Percent Difference from Freeway/Expressway ESALs by Road Class**

## 5.2 Roadway Deflection and Non-Linearity Structural Index

In addition to roadway deflection, the City of Saskatoon asset management study also utilized PSIPave Structural Indices (SI) to rank the structural integrity of roadways with consideration to deformation, non-linear elastic primary responses, local field state conditions and surface deterioration (PSI 2007). The PSIPave SI were measured in the same locations as the deflection response measurements, outlined in Table 5.6. Measurements from Circle Drive eastbound between Faithfull Avenue and Avenue C were omitted because the roadway consisted of jointed plain concrete pavement and were not representative of flexible pavement responses.

**Table 5.6 - Urban Roadway PSIPave Structural Indices under Primary Loading**

| Road Name | Location | Primary Loading SI EB/SB CL | EB/SB ML | WB/NB ML | WB/NB CL |
|---|---|---|---|---|---|
| **FREEWAY/EXPRESSWAY ROADS** | | | | | |
| Circle Drive | W Bridge Abutment to Median Gore | 111 | 113 | 74 | 115 |
| | Median Gore Point to Millar Ave | 180 | 115 | 110 | 103 |
| | Millar Ave to 1st Ave N | 157 | 146 | 189 | 130 |
| | 1st Ave N to Faithfull Ave | 85 | 171 | 177 | 149 |
| | Faithfull Ave to E Bridge Abutment | - | - | 158 | 230 |
| | E Bridge Abutment to Ave C | - | - | 210 | 220 |
| | Average | 133 | 136 | 153 | 158 |
| **ARTERIAL ROADS** | | | | | |
| 8th Street | Boychuk Dr to McKercher Dr | 93 | 127 | 98 | 71 |
| Attridge Dr | McOrmond Dr to Kenderdine Rd | 80 | 75 | 71 | 86 |
| | Kenderdine Rd to Berini Dr | 58 | 49 | 69 | 49 |
| | Berini Dr to Central Ave | 84 | 79 | 72 | 92 |
| Ave C | Circle Dr to 47th St | 77 | 95 | 128 | 74 |
| Preston Ave | 8th St to Main St | 68 | - | - | 95 |
| | Main St to 14th St | 61 | - | - | 78 |
| | Average | 74 | 85 | 88 | 78 |
| **LOCAL-INDUSTRIAL ROADS** | | | | | |
| Idylwyld Dr Service Rd | 60th St to 71st St | 264 | - | - | 264 |
| Edson St | Jasper Ave to Portage Ave | 134 | - | - | 134 |
| Jasper Ave | Melville St to Edson St | 146 | - | - | 146 |
| Portage Ave | Melville St to Edson St | 117 | - | - | 117 |
| | Average | 165 | - | - | 165 |
| **LOCAL & COLLECTOR ROADS** | | | | | |
| Kenderdine Rd | 115th St to Attridge Dr | 45 | - | - | 32 |
| 31st St | Ave R to Ave W | 50 | - | - | 50 |
| Adelaide St | McKinnon Ave to Haultain Ave | 25 | - | - | 25 |
| Rylston Rd | Witney Ave to Ave X | 43 | - | - | 43 |
| | Average | 41 | - | - | 38 |

The PSIPave SI became smaller towards the Circle Drive Bridge, as shown in Table 5.6, with SI ranging from 74 and 230. The average PSIPave SI across all lanes in both travel directions on Circle Drive was 147 with a standard deviation of 45, as presented in Table 5.7 and Figure 5.7.

The urban arterial PSIPave SI ranged from 49 to 128, as shown in Table 5.6, with the lowest SI results typically occurring in the curb lanes. The mean arterial PSIPave SI and standard deviation were 80 and 20, as presented in Table 5.7 and Figure 5.7.

Local-industrial roadway SI ranged from 117 to 264 and exhibited an average SI of 165 with a standard deviation of 62. The local-industrial roadways generally exhibited PSIPave SI results that were indicative of stronger structural integrity than those observed on Circle Drive. However, since the local-industrial roadways within the test group had either been recently rehabilitated and/or maintained at a higher level to facilitate truck traffic, their PSIPave SI were most likely higher than would be expected. As such, it was speculated that typical PSIPave SI of 100 to 130 would generally be anticipated on urban local-industrial roadways.

Only one collector roadway was assessed, producing lower PSIPave SI of 32 to 45. Three local roadways were tested, producing PSIPave SI ranging from 25 to 50. The collector roadway exhibited PSIPave SI that was congruous with the local roadways. As such, the two road types were combined to create a new category of roadway (local & collector) with a mean PSIPave SI of 39 and a standard deviation of 10.

**Table 5.7 - Urban Roadway PSIPave Structural Index Analysis by Road Class**

| Road Type | Mean PSIPave Structural Index | St. Dev. | CV |
|---|---|---|---|
| Freeway/Expressway | 147 | 45 | 30% |
| Arterial | 80 | 20 | 25% |
| Local-Industrial | 165 | 62 | 37% |
| Local & Collector | 39 | 10 | 26% |

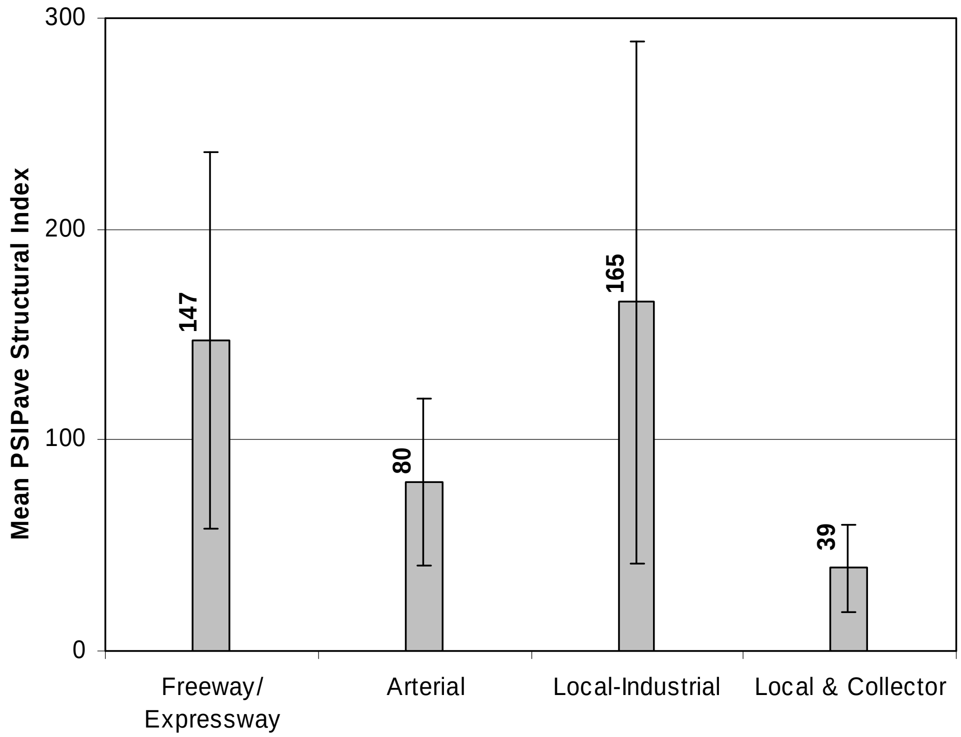


**Figure 5.7 - Mean PSIPave Structural Index by Road Class (± 2 St. Dev.)**

Creating a ratio of the various urban road type PSIPave SI with the freeway/expressway SI as a baseline offered a comparative estimate of the probable loading responses attainable on urban roadways. Whereas the deflection ratios only took into account pavement deflections due to loading, PSIPave SI ratios also considered potential pavement strengthening or weakening due to non-linear elastic pavement responses to loading (Prang et al. 2007).

The range of urban roadway SI were compared by road type using the same ratio comparison method utilized for the deflection analysis, as illustrated in Equations 5.3 and 5.4.

Given that a larger PSIPave SI equates to a stronger pavement structure, the range of structural index ratios were assessed by inverting the ratio of freeway/expressway to road type to produce results greater than 1, as illustrated in Equations 5.3 and 5.4.

$$\textit{PSIPave SI ratio} = \frac{SI_{Freeway/Expressway}}{SI_i} \quad [5.3]$$

Where:

$SI_i$ = the mean PSIPave SI obtained under primary loads for test road i;

$SI_{Freeway/Expressway}$ = the mean PSIPave SI obtained under primary loads for the freeway and expressway sample.

$$\textit{PSIPave SI ratio range} = \frac{SI_{Freeway/Expressway}}{SI_i \pm 2\sigma_i} \quad [5.4]$$

Where:

$SI_i$ = the mean PSIPave SI obtained under primary loads for test road i;

$\sigma_i$ = the standard deviation of the PSIPave SI obtained under primary loads for road class i;

$SI_{Freeway/Expressway}$ = the mean PSIPave SI obtained under primary loads for the freeway and expressway sample.

The PSIPave SI ratios for the various urban road types are summarized in Table 5.8 and Figure 5.8. As illustrated in Figure 5.8, the largest range in PSIPave SI ratio was observed for the local and collector roadways at 5.5, followed by local-industrial roadways at 3.1. The mean SI of the local-industrial road class was less than the freeway/expressway baseline, which indicated that these road types typically had pavement structures that were stronger than the freeway/expressway structures. As noted previously, these results were anticipated due to the recent reconstruction and/or base strengthening of the local-industrial roadways tested in the City of Saskatoon asset management study. However, the total range of SI ratio for this road class indicated that local-industrial roadways had the potential to be much weaker than freeway/expressway pavements.

**Table 5.8 - Roadway PSIPave Structural Index Ratios**

| Roadway | Mean PSIPave SI Ratio | Mean PSIPave SI Ratio - 2 St. Dev. | Mean PSIPave SI Ratio + 2 St. Dev. |
|---|---|---|---|
| Freeway/Expressway | 1.0 | - | - |
| Arterial | 1.8 | 3.6 | 1.2 |
| Local-Industrial | 0.9 | 3.6 | 0.5 |
| Local & Collector | 3.8 | 8.0 | 2.5 |

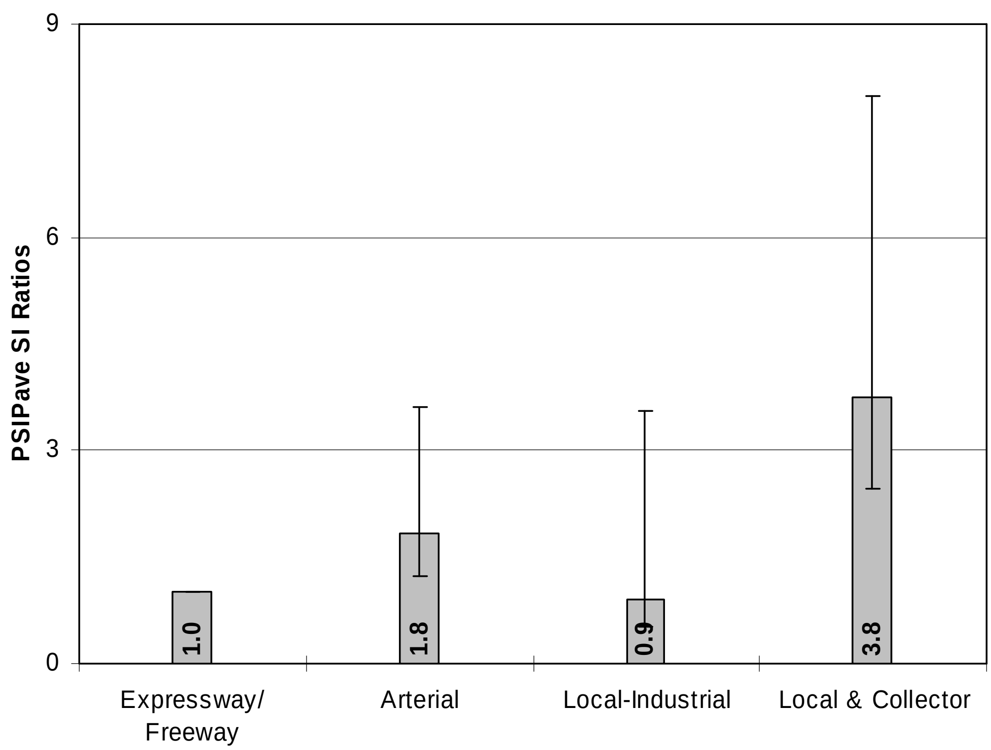


**Figure 5.8 – PSIPave Structural Index Ratios by Urban Road Class (± 2 St. Dev.)**

PSIPave SI ratios were combined with the mean GVW ESAL spectra developed in Chapter 4 to generate the ESALs by road class, as summarized in Table 5.9 and Figure 5.9. Similar to the deflection results, the mean GVW ESALs typically increased as the urban road classification moved from freeway/expressway to local, with the largest increase noted for local and collector roadways. Local-industrial roadways exhibited mean ESALs that were typically less than the freeway/expressway baseline ESALs, as indicated in the ratio trends illustrated in Figure 5.8.

**Table 5.9 – PSIPave Structural Index Mean GVW ESALs by Road Class**

| Mean GVW ESALs | Freeway/ Expressway | Arterial | Local-Industrial | Local & Collector |
|---|---|---|---|---|
| Class 4 | 0.9 | 1.7 | 0.8 | 3.4 |
| Class 5 | 1.2 | 2.2 | 1.1 | 4.4 |
| Class 6 | 1.4 | 2.6 | 1.3 | 5.3 |
| Class 11 | 0.4 | 0.7 | 0.4 | 1.5 |
| Class 12 | 1.6 | 3.0 | 1.4 | 6.1 |
| Class 13 | 1.7 | 3.1 | 1.5 | 6.4 |
| Class 19 | 3.3 | 5.9 | 2.9 | 12.2 |

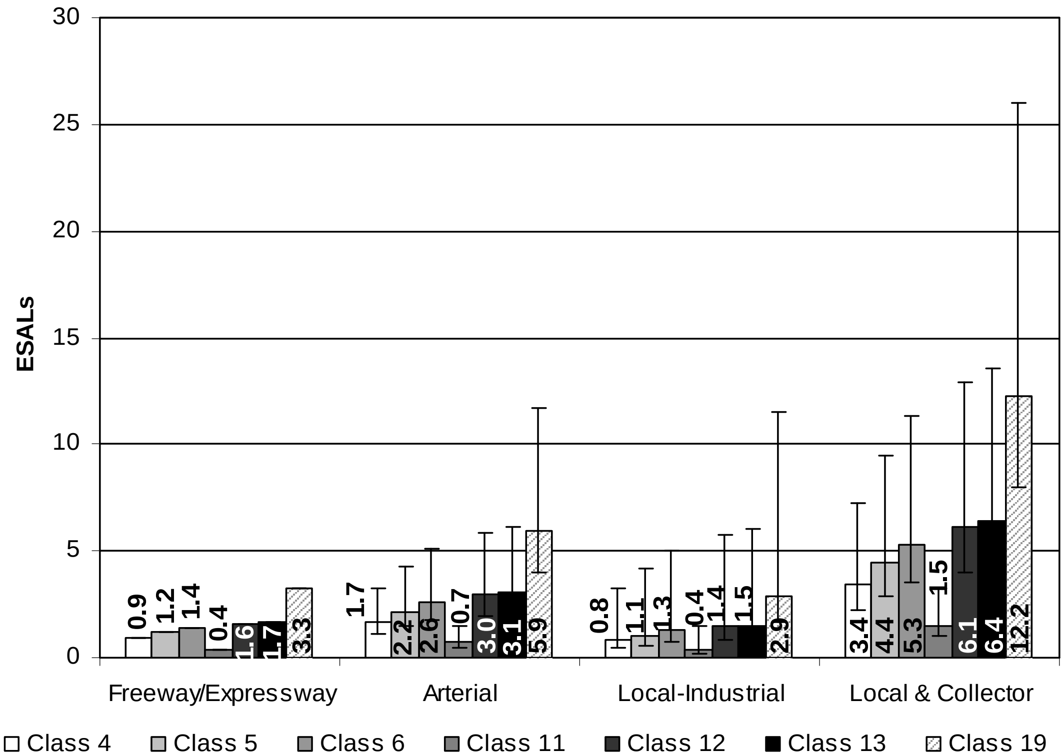


**Figure 5.9 - Mean GVW ESALs per PSIPave SI Ratio (± 2 St. Dev. PSIPave SI Ratio)**

As seen in Table 5.10 and Figure 5.10, local and collector roadways exhibited the largest percent increase in ESALs compared to the freeway/expressway with an average increase of 276 percent above baseline. Arterial roadways followed with an average increase of 83 percent over the freeway/expressway baseline. Local-industrial roadways displayed an 11 percent decrease in ESALs compared to the baseline freeway/expressway ESALs, which was indicative of stronger pavement structures due to structural rehabilitation and/or base strengthening.

**Table 5.10 - Percent Difference in PSIPave Structural Index Ratio by Urban Road Class**

| Roadway | Mean PSIPave SI Ratio | Mean – 2 St. Dev. PSIPave SI Ratio | Mean + 2 St. Dev. PSIPave SI Ratio |
|---|---|---|---|
| Arterial | 83% | 260% | 23% |
| Local-Industrial | -11% | 256% | -49% |
| Local & Collector | 276% | 699% | 146% |

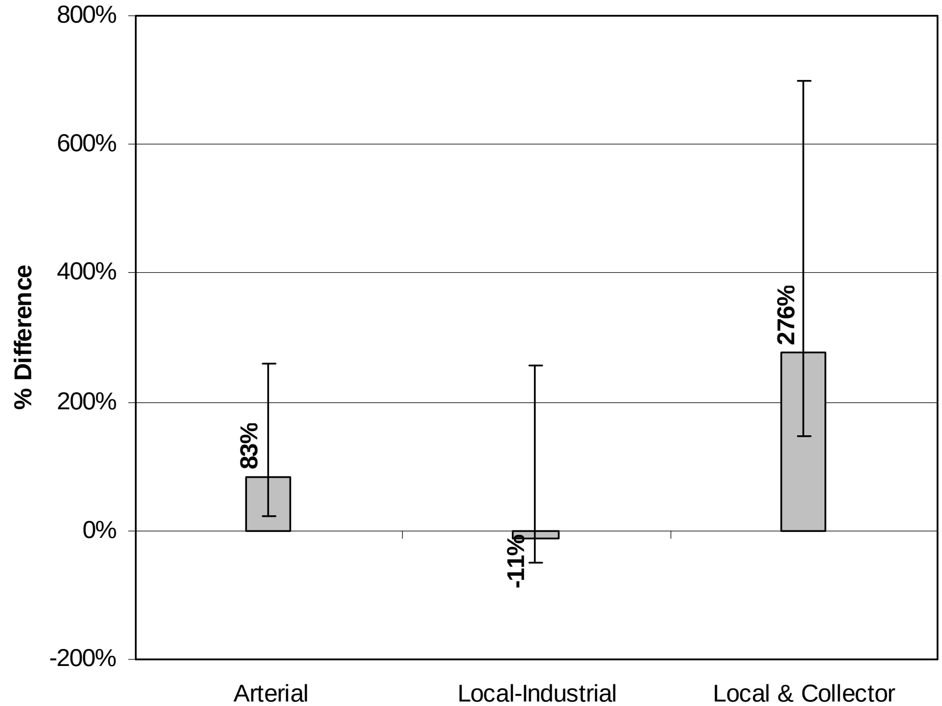


**Figure 5.10 – PSIPave SI Ratio ESAL Difference from Freeway/Expressway ESALs (± 2 St. Dev.)**

## 5.3 Deflection vs. Structural Index Ratio Relationships

A comparison of the ESAL ratios obtained from the deflection and PSIPave Structural Index testing results is summarized in Table 5.11 and Figure 5.11. As presented in Table 5.11 and Figure 5.11, the mean and mean less 2 standard deviations arterial GVW ESALs were the same for both ratio methods, with a mean of 1.8 ESALs and lower range of 1.2 ESALs. However, the PSIPave SI ratio resulted in an upper ESAL range across all road types that were greater than those obtained from deflection ratio analysis. Larger ESAL ranges were obtained using the PSIPave SI ratio method because it took into account both deflection and potential strengthening or weakening of the asphaltic materials due to non-linear elastic responses to load (Prang et al. 2007).

Table 5.11 – Deflection Ratio vs. PSIPave Structural Index Ratio ESALs

| | DEFLECTION RATIO | | | PSIPAVE SI RATIO | | |
|---|---|---|---|---|---|---|
| **Road Type** | **Mean** | **Mean + 2 St.Dev.** | **Mean – 2 St.Dev.** | **Mean** | **Mean + 2 St.Dev.** | **Mean – 2 St.Dev.** |
| Freeway/Expressway | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| Arterial | 1.8 | 2.3 | 1.2 | 1.8 | 3.6 | 1.2 |
| Local-Industrial | 1.3 | 1.6 | 1.0 | 0.9 | 3.6 | 0.5 |
| Local & Collector | 2.9 | 4.9 | 0.9 | 3.8 | 8.0 | 2.5 |

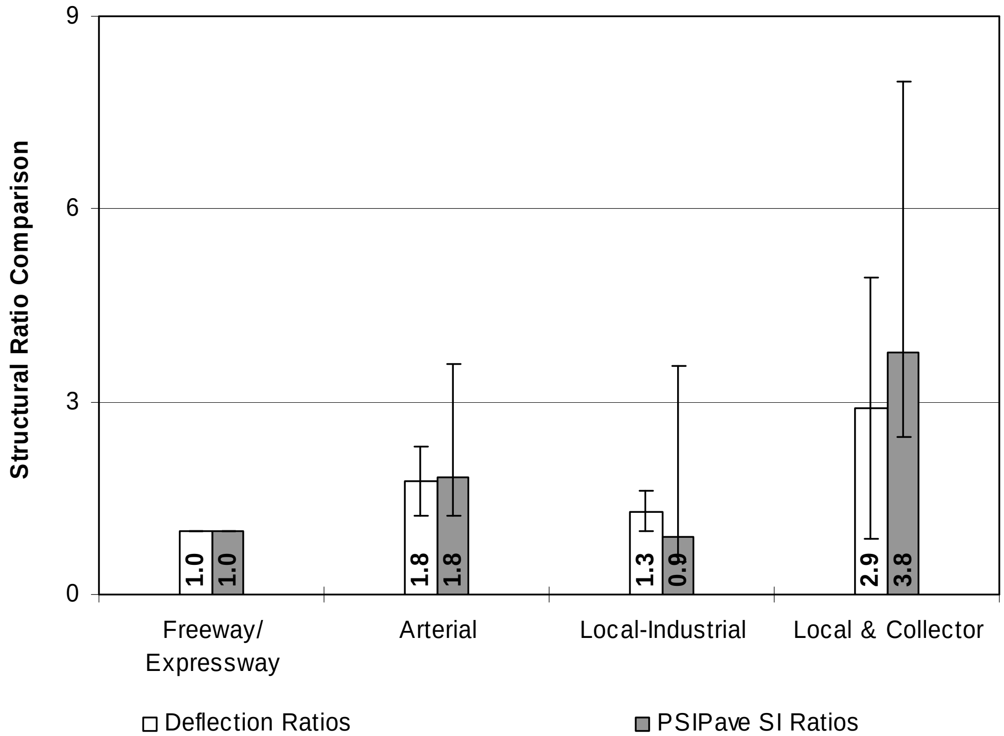


**Figure 5.11 – Deflection Ratio vs. PSIPave Structural Index Ratio ESALs (± 2 Ratio St. Dev.)**

The sensitivity of PSIPave Structural indices to asphaltic material loading responses was emphasized through comparison of the ESALs obtained for local-industrial roadways, as illustrated in Table 5.11 and Figure 5.11. The local-industrial deflection-based ESALs showed that this road type exhibited deflections that were only marginally greater than those observed on Circle Drive, indicating that local-industrial roadways were slightly weaker than the freeway/expressway baseline. Conversely, the PSIPave Structural Index ratio resulted in a mean of 0.9 ESALs, indicating that local-industrial roadways were capable of handling greater loads than the freeway/expressway baseline. The difference in ESALs was due to the PSIPave SI inclusion of asphaltic material responses.

Comparison of the ESALs generated through deflection vs. PSIPave SI ratio methods, summarized in Table 5.11 and Figure 5.11, indicated disparities between both the mean GVW and range of local and collector ESALs. The mean GVW ESALs and ESAL ranges were higher for the PSIPave SI ratio method than for the deflection ratio method, with an upper range that was nearly twice as large as that obtained using the deflection method. This result may have been due to the sensitivity of the PSIPave SI ratio to strain-weakening as observed for the arterial road classes.

Comparison of the percent difference between the urban ESALs and the freeway/expressway baseline ESAL spectra is summarized in Table 5.12 and Figure 5.12. With the exception of local-industrial road types, the PSIPave SI ratio method of calculating urban ESALs generally exhibited greater increases from the baseline than the deflection ratio method. As observed earlier, this increase was due to the PSIPave SI incorporation of the effects of strain-hardening and weakening from the application of loadings. The structural index ratio method also exhibited increased variation amongst pavement strengths, resulting in greater ranges of ESALs by road type.

Both the local-industrial and the local and collector road types had the potential for ESALs that were smaller than those obtained on the freeway/expressway sample road, as demonstrated by the negative lower two standard deviation ranges for these road types in Table 5.12 and Figure 5.12. The results of both the deflection and PSIPave SI ESALs calculations indicated that ESALs on different urban road types would most likely be larger than those from the freeway/expressway baseline, ranging from 83 percent larger on arterial roads to 276 percent larger on local & collector roads.

**Table 5.12 – Percent Difference in Ratio ESALs from Baseline Freeway/Expressway ESALs**

| GVW ESAL Factors | Arterial | Local-Industrial | Local & Collector |
|---|---|---|---|
| Mean Deflection | 76% | 30% | 190% |
| Mean Deflection + 2 St. Dev. | 130% | 61% | 392% |
| Mean Deflection - 2 St. Dev. | 21% | -2% | -13% |
| Mean PSIPave SI | 83% | -11% | 276% |
| Mean PSIPave SI + 2 St. Dev. | 23% | -49% | 146% |
| Mean PSIPave SI - 2 St. Dev. | 260% | 256% | 699% |

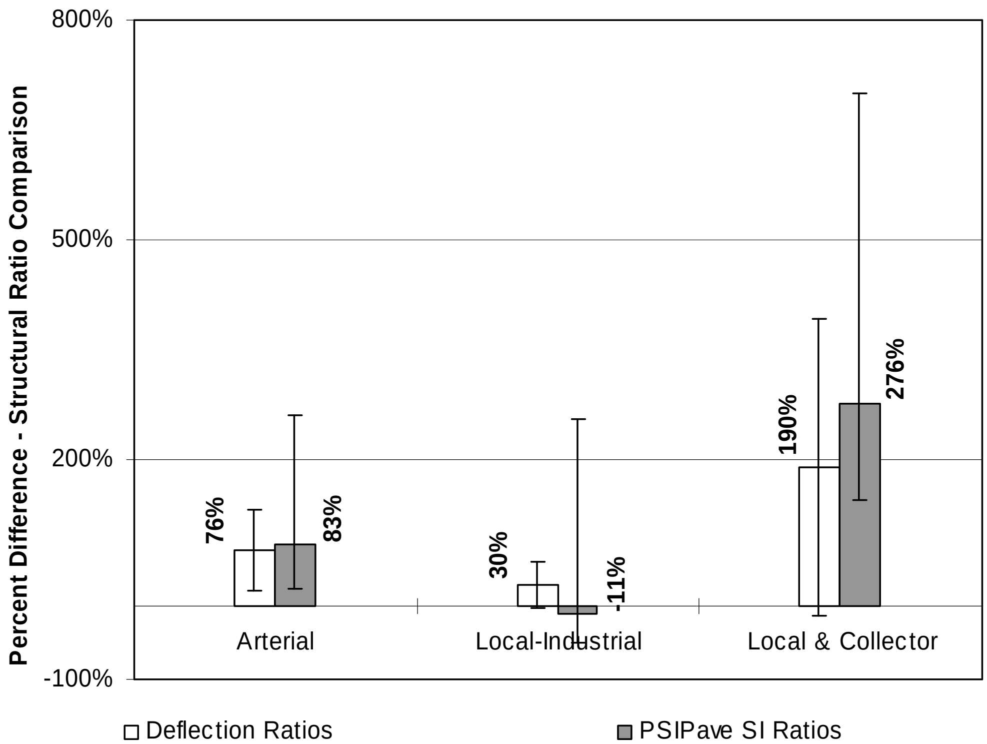


**Figure 5.12 – Difference in PSIPave SI and Deflection ESALs from Freeway/Expressway ESALs (± 2 St. Dev.)**

Class 19 ESALs were calculated from deflection and PSIPave SI ratios to further illustrate the difference between the two urban ESAL calculation methods. As shown in Table 5.13 and Figure 5.13, Class 19 urban arterial ESALs obtained by the deflection ratio had a mean of 5.7 ESALs with upper and lower two standard deviation ranges of 3.9 to 7.5 ESALs. Class 19

PSIPave SI urban arterial ESALs had a mean of 5.9 ESALs a range of 4.0 to 11.7 ESALs. Though both urban ESAL calculation methods had similar mean results, the PSIPave SI method accommodated for potential strain-weakening that may occur from the application of load. The incorporation of this additional factor resulted in an upper range that was more than 50 percent greater than the upper range of the deflection ESALs. Similarly, the PSIPave SI Class 19 local and collector mean ESALs were 30 percent greater than the deflection ESALs, with upper and lower ranges that were 63 percent to 186 percent greater than those observed for the deflection ratio.

The mean PSIPave SI Class 19 local-industrial ESALs were less than both the deflection-based ESALs and the freeway/expressway baseline, at 2.9 as compared to 4.2 and 3.3 ESALs. Due to the incorporation of non-linear elastic asphaltic material responses to loading, the range between the upper and lower equivalent loads was greater for the PSIPave SI ESALs than for the deflection-based ESALs.

**Table 5.13 - PSIPave Structural Index and Deflection Ratio Class 19 ESALs**

| | DEFLECTION RATIO | | | PSIPAVE SI RATIO | | |
|---|---|---|---|---|---|---|
| **Road Type** | **Mean** | **Mean + 2 St. Dev.** | **Mean – 2 St. Dev.** | **Mean** | **Mean + 2 St. Dev.** | **Mean – 2 St. Dev.** |
| Express/Freeway | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 | 3.3 |
| Arterial | 5.7 | 7.5 | 3.9 | 5.9 | 11.7 | 4.0 |
| Local-Industrial | 4.2 | 5.2 | 3.2 | 2.9 | 11.6 | 1.7 |
| Local & Collector | 9.4 | 16.0 | 2.8 | 12.2 | 26.0 | 8.0 |

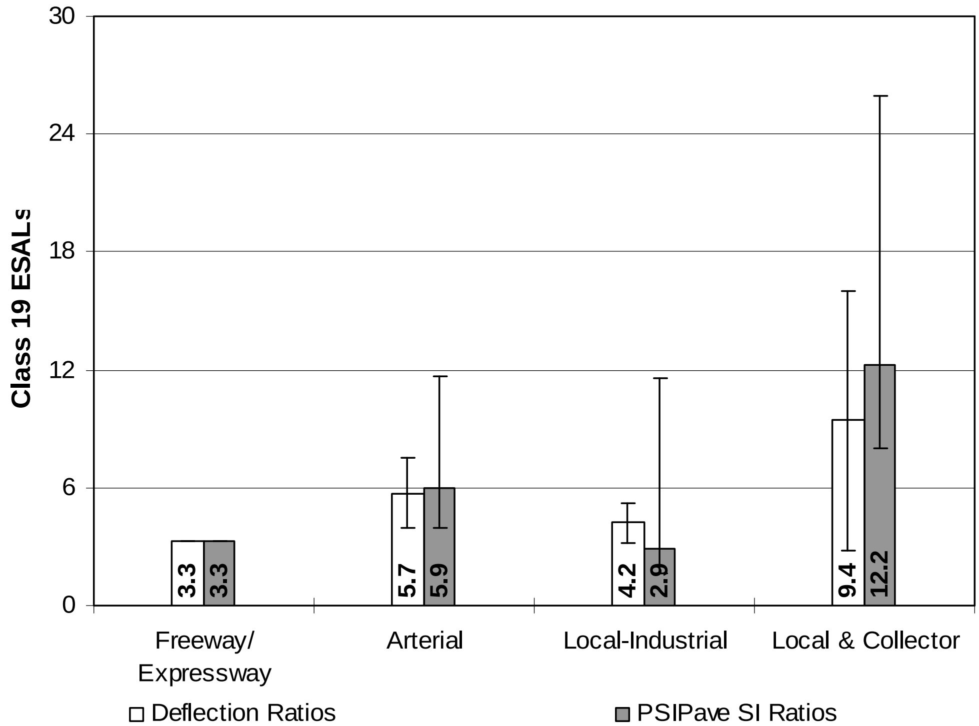


**Figure 5.13 - PSIPave Structural Index and Deflection Ratio Class 19 ESALs**

## 5.4 Mechanistic-Empirical ESALs for Urban Roadways Summary

The City of Saskatoon completed an asset management structural study across city roadways in 2006. GPR was utilized to evaluate surface deterioration and dielectric permittivity profiles, and HWD was utilized to assess non-linear elastic pavement responses, including strain-hardening and weakening behaviours (PSI 2007). Several measures of roadway deflection and non-linear elastic pavement responses were obtained for a range of weights based on secondary and primary weight limits for various urban road types, including:

- Expressways and freeways;
- Arterials;
- Collectors and locals, and;
- Local-Industrials.

Given the limitations of conventional ESAL calculations when applied to urban pavements, this research attempted to formulate load equivalencies based on the structural responses obtained in the 2006 City of Saskatoon asset management study. ESALs were calculated by vehicle and urban road type through the combination of an urban roadway primary response ratio with an ESAL spectra obtained from an urban freeway/expressway.

ESAL relationships, developed using the mean deflections from different urban roads, were shown to increase as the urban road classification shifted from freeway and expressway to local. The increase was indicative of greater pavement deflection under primary weights and correlated to a thinning of the overall pavement structure as testing shifted from freeways/expressways to local roadways. The range of deflection, represented by the mean ± two standard deviations, was greater for local and collector road types than the other urban roadways. The greater range of deflection indicated that more structural variation was present within the lower volume and thinner structure urban roadways. Local and collector road types exhibited the greatest increase in ESALs as compared to freeway/expressway baseline ESALs.

Urban roadway PSIPave SI were compared using the range of PSIPave SI obtained near the Circle/Preston VWIM site for a baseline.The greatest range in PSIPave SI ratio was observed for local and collector road types, followed by local-industrial roadways. The mean local-industrial PSIPave SI was less than the freeway/expressway baseline, indicating that the average local-industrial roadway had a stronger pavement structure than the average freeway/expressway. However, the maximum local-industrial PSIPave SI ratio reached 3.6, indicating that these roadways could be much weaker than their freeway/expressway counterparts. The local-industrial roadways tested by the City of Saskatoon for the 2006 structural assessment had recently received either rehabilitation and/or base strengthening. As such, structural testing completed across a larger range of local-industrial roadways within the City would most likely produce PSIPave SI ratio ranging from 1 (freeway/expressway baseline) to 1.8 (arterial roadways).

Comparison of the difference between urban roadway ESALs and the freeway baseline ESAL spectra indicated that the PSIPave SI ratio produced the larger urban load equivalencies. The larger loads were a result of the PSIPave SI consideration of non-linear elastic asphalt responses. As such, comparison of the two ratio methods indicated that the PSIPave SI method provided urban ESALs that were more reflective of the responses of urban pavement structures to loading. However, both ESAL calculation methods indicated that loads on urban roadways would typically be larger than those observed on a freeway or expressway, with loads ranging from 83 percent larger on arterial roads to 276 percent larger on local and collector roads.

# CHAPTER 6 - MECHANISTIC-EMPIRICAL URBAN ESALFS FOR DESIGN

Urban ESALs were generated in Chapter 5 by combining the commercial vehicle load spectra from Chapter 4 with the results of the 2006 City of Saskatoon roadway structural assessment study. Urban ESALs were developed for deflection and PSIPave SI pavement responses of the urban roadways with freeway and expressway structural responses utilized as a baseline representative of a typical highway structure. Comparison of deflection-based vs. PSIPave SI-based ratios concluded that the PSIPave SI ratios were more reflective of the responses of different urban pavement structures to loading. The improved representation was because the PSIPave SI method not only took into consideration deflections due to loading, but also considered non-linear elastic responses of the pavement materials resulting from loading (i.e.: strength-hardening and/or weakening).

This chapter presents urban ESAL factors (ESALFs) based on the PSIPave SI ratios for typical urban road structures within the City of Saskatoon. The ESALF tables presented herein were constructed based on AASHTO load equivalencies for the Circle/Preston VWIM site freeway pavement structure and include the load spectra generated for the City of Saskatoon. The tables are grouped by road type and are representative of the full range of roadway structural performance as per the results of the non-destructive testing completed for the 2006 City of Saskatoon comprehensive roadway structural assessment. Axle weights were represented using kips for ease of comparison with the AASHTO load equivalency tables.

### 6.1 Local-Industrial Roadway Urban ESALFs

Roadways measured for the local-industrial road type category generally exhibited good surface conditions due to recent structural rehabilitation and/or base strengthening, as illustrated in Figures 6.1 and 6.2.

**Figure 6.1 – Edson Street (June 13, 2006), PSI Inc.**

**Figure 6.2 – Jasper Street (June 12, 2006), PSI Inc.**

As presented in Tables 6.1 through 6.3 and Figures 6.3 through 6.5, the PSIPave SI single, tandem and tridem axle load equivalencies for local-industrial roads were less than the AASHTO load equivalencies for the Circle/Preston VWIM freeway site. Lower urban load equivalencies indicated that the local-industrial roadways tested in the 2006 assessment were stronger than the baseline freeway and expressway. However, the local-industrial roadways included in the testing had all received recent rehabilitation and/or base strengthening. Consequently, the non-destructive testing results were better than would normally be expected and it is anticipated that the average local-industrial roadway would produce PSIPave SI somewhere between the values representative of major arterials and those representative of freeways and expressways.

The mean single axle loads across the seven vehicle configurations of the Chapter 4 load spectra ranged from 8 to 16 kips and correlated to AASHTO load equivalencies ranging from 0.047 to 0.613 per single axle group on the freeway structure, as highlighted in grey in Table 6.1. Based on the PSIPave SI results, the mean local-industrial roadway single axle group load equivalencies ranged from 0.042 to 0.546 per single axle, with upper and lower (±two SI standard deviations) equivalencies ranging from 0.024 to 2.18 per single axle.

The potential range of local-industrial single axle group loads is outlined in Table 6.1 and was generated using the minimum and maximum loads from the Chapter 4 load spectra. The single axle loads in the load spectra ranged from a minimum of 2 kips to a maximum of 28 kips per single axle. This correlated to AASHTO load equivalencies ranging from 0.0004 to 6.98 per single axle group on the freeway structure. This range was equivalent to mean local-industrial single axle group loads ranging from 0.0004 to 6.21 per single axle group with a lower and upper range of 0.0002 to 24.8 per group.

**Table 6.1 –Local-Industrial Roadway Single Axle Group Urban ESALFs**

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Local-Industrial ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0004 | 0.0002 | 0.0004 | 0.001 |
| 4 | 0.004 | 0.002 | 0.004 | 0.014 |
| 6 | 0.017 | 0.009 | 0.015 | 0.060 |
| **8** | **0.047** | **0.024** | **0.042** | **0.167** |
| **10** | **0.102** | **0.052** | **0.091** | **0.363** |
| **12** | **0.198** | **0.101** | **0.176** | **0.704** |
| **14** | **0.358** | **0.182** | **0.319** | **1.27** |
| **16** | **0.613** | **0.312** | **0.546** | **2.18** |
| 18 | 1.00 | 0.509 | 0.890 | 3.56 |
| 20 | 1.57 | 0.799 | 1.40 | 5.58 |
| 22 | 2.38 | 1.21 | 2.12 | 8.46 |
| 24 | 3.49 | 1.78 | 3.11 | 12.4 |
| 26 | 4.99 | 2.54 | 4.44 | 17.7 |
| 28 | 6.98 | 3.55 | 6.21 | 24.8 |
| 30 | 9.50 | 4.83 | 8.46 | 33.8 |
| 32 | 12.8 | 6.51 | 11.4 | 45.5 |
| 34 | 16.9 | 8.60 | 15.0 | 60.1 |
| 36 | 22.0 | 11.2 | 19.6 | 78.2 |
| 38 | 28.3 | 14.4 | 25.2 | 100.6 |
| 40 | 35.9 | 18.3 | 32.0 | 127.6 |
| 42 | 45.0 | 22.9 | 40.1 | 160.0 |
| 44 | 55.9 | 28.4 | 49.8 | 198.7 |
| 46 | 68.8 | 35.0 | 61.2 | 244.6 |
| 48 | 83.9 | 42.7 | 74.7 | 298.3 |
| 50 | 102.0 | 51.9 | 90.8 | 362.6 |

As seen in Figure 6.3, the upper bounds of the local-industrial single axle load equivalencies represent the poorest roadway structural performance and exhibited an increase of nearly 600 percent over the excellently-performing (lower) bounds. The large range between upper and lower load equivalencies is representative of disparities between pavement loading responses due to historical variations in vehicle usage, structural composition and construction materials. The maximum load equivalency for new or structures in excellent condition were 50 percent less than the standard AASHTO load equivalencies. The poorly performing road structures rendered minimum load equivalency factors approximately 250 percent greater than those calculated using the AASHTO method.

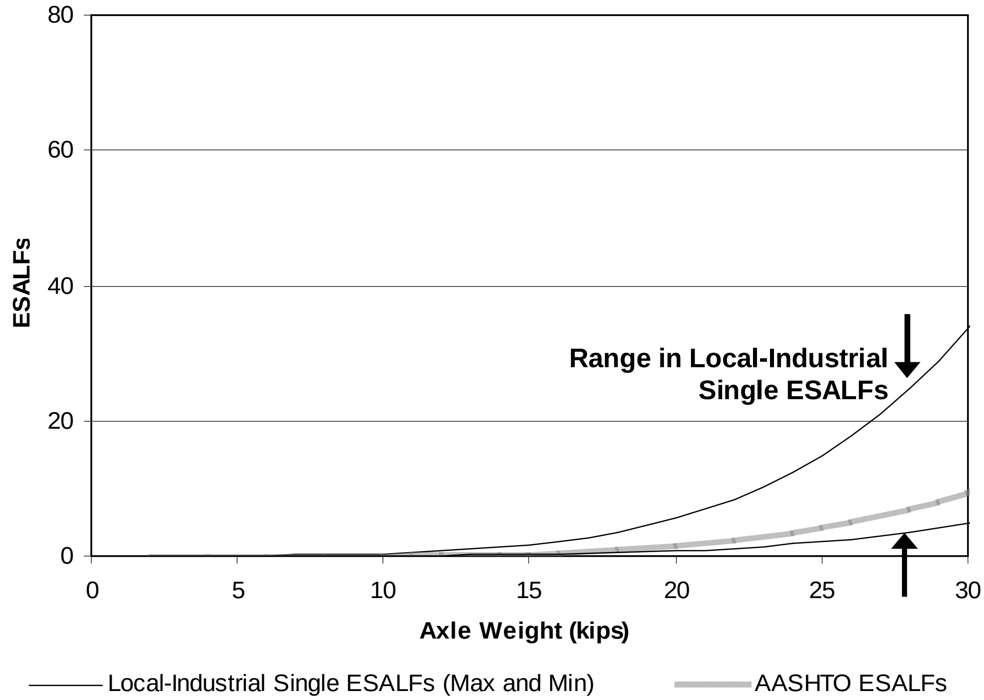


**Figure 6.3 –Local-Industrial Roadway Single Axle Group Urban ESALFs**

Table 6.2 and Figure 6.4 illustrate the range of urban local-industrial tandem axle load equivalencies across the observed range of PSIPave SI ratios. The mean tandem axle loads across the seven configurations in the Chapter 4 load spectra ranged from 22 to 34 kips and correlated to AASHTO load equivalencies ranging from 0.198 to 1.08 per tandem axle, as highlighted in grey in Table 6.2. Based on the PSIPave SI results, the mean urban local-industrial tandem axle group load equivalencies ranged from 0.176 to 0.961 per single axle, with upper and lower (±two SI ratio standard deviations) equivalencies ranging from 0.101 to 3.84 per tandem axle.

**Table 6.2 –Local-Industrial Roadway Tandem Axle Group Urban ESALFs**

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Local-Industrial ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0001 | 0.0001 | 0.0001 | 0.0004 |
| 4 | 0.001 | 0.0003 | 0.0004 | 0.0018 |
| 6 | 0.002 | 0.001 | 0.002 | 0.007 |
| 8 | 0.006 | 0.003 | 0.005 | 0.021 |
| 10 | 0.013 | 0.007 | 0.012 | 0.046 |
| 12 | 0.024 | 0.012 | 0.021 | 0.085 |
| 14 | 0.041 | 0.021 | 0.036 | 0.146 |
| 16 | 0.065 | 0.033 | 0.058 | 0.231 |
| 18 | 0.097 | 0.049 | 0.086 | 0.345 |
| 20 | 0.141 | 0.072 | 0.126 | 0.501 |
| **22** | **0.198** | **0.101** | **0.176** | **0.704** |
| **24** | **0.273** | **0.139** | **0.243** | **0.971** |
| **26** | **0.370** | **0.188** | **0.329** | **1.32** |
| **28** | **0.493** | **0.251** | **0.439** | **1.75** |
| **30** | **0.648** | **0.330** | **0.577** | **2.30** |
| **32** | **0.843** | **0.429** | **0.750** | **3.00** |
| **34** | **1.08** | **0.549** | **0.961** | **3.84** |
| 36 | 1.38 | 0.702 | 1.23 | 4.91 |
| 38 | 1.73 | 0.880 | 1.54 | 6.15 |
| 40 | 2.16 | 1.10 | 1.92 | 7.68 |
| 42 | 2.67 | 1.36 | 2.38 | 9.49 |
| 44 | 3.27 | 1.66 | 2.91 | 11.6 |
| 46 | 3.98 | 2.02 | 3.54 | 14.1 |
| 48 | 4.80 | 2.44 | 4.27 | 17.1 |
| 50 | 5.76 | 2.93 | 5.13 | 20.5 |
| 52 | 6.87 | 3.50 | 6.12 | 24.4 |
| 54 | 8.14 | 4.14 | 7.25 | 28.9 |
| 56 | 9.60 | 4.88 | 8.55 | 34.1 |
| 58 | 11.3 | 5.75 | 10.1 | 40.2 |
| 60 | 13.1 | 6.66 | 11.7 | 46.6 |
| 62 | 15.3 | 7.78 | 13.6 | 54.4 |
| 64 | 17.6 | 8.95 | 15.7 | 62.6 |
| 66 | 20.3 | 10.3 | 18.1 | 72.2 |
| 68 | 23.3 | 11.9 | 20.7 | 82.8 |
| 70 | 26.6 | 13.5 | 23.7 | 94.6 |
| 72 | 30.3 | 15.4 | 27.0 | 107.7 |
| 74 | 34.4 | 17.5 | 30.6 | 122.3 |
| 76 | 38.9 | 19.8 | 34.6 | 138.3 |
| 78 | 43.9 | 22.3 | 39.1 | 156.1 |
| 80 | 49.4 | 25.1 | 44.0 | 175.6 |
| 82 | 55.4 | 28.2 | 49.3 | 197.0 |
| 84 | 61.9 | 31.5 | 55.1 | 220.1 |
| 86 | 69.1 | 35.2 | 61.5 | 245.7 |
| 88 | 76.9 | 39.1 | 68.5 | 273.4 |
| 90 | 85.4 | 43.4 | 76.0 | 303.6 |

The potential range of local-industrial tandem axle loads is outlined in Table 6.2 and Figure 6.4, and was generated using the minimum and maximum loads from the Chapter 4 load spectra. The tandem axle loads from the spectra ranged from a minimum of 2 kips to a maximum of 54 kips per tandem axle, and correlated to AASHTO load equivalencies ranging from 0.0001 to 8.14 per tandem axle group on the freeway structure. This range corresponded to mean local-industrial tandem axle group load equivalencies ranging from 0.0001 to 7.25 per tandem axle group with a lower and upper range of 0.0001 to 28.9 per group.

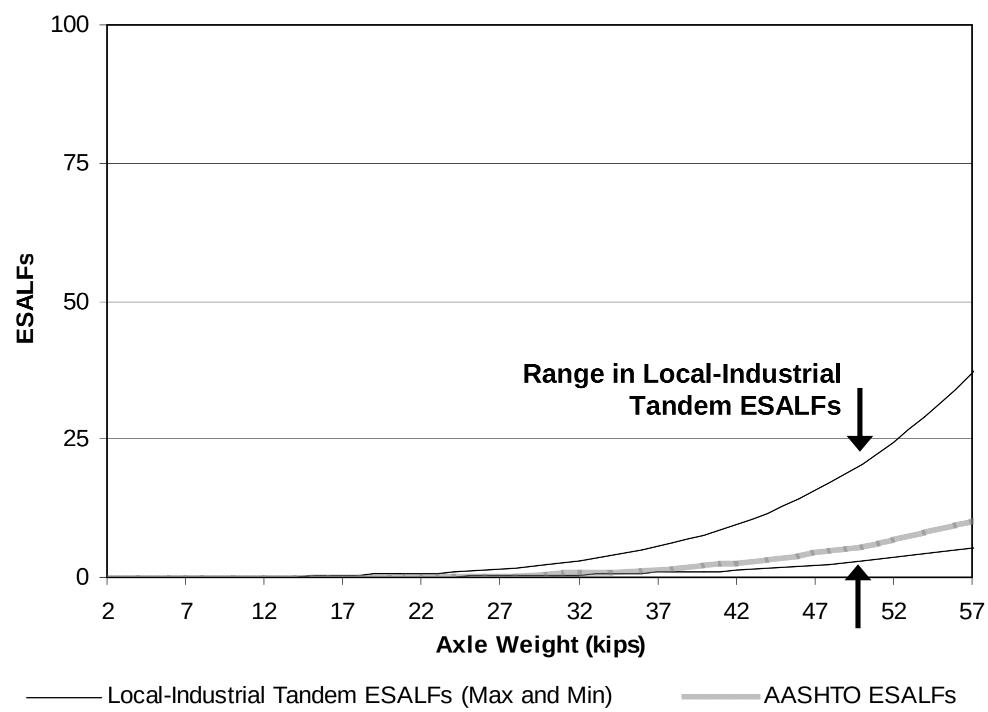


**Figure 6.4 –Local-Industrial Roadway Tandem Axle Group Urban ESALFs**

Table 6.3 and Figure 6.5 illustrate the range of urban local-industrial tridem axle load equivalencies for the PSIPave SI ratios. The mean tridem axle loads from the Chapter 4 load spectra ranged from 42 to 46 kips and correlated to AASHTO load equivalencies ranging from 0.594 to 0.854 per tridem group, as highlighted in Table 6.3. Based on the PSIPave SI results, the mean local-industrial tridem axle load equivalencies ranged from 0.529 to 0.760 per tridem axle, with upper and lower (±two SI ratio standard deviations) equivalencies ranging from 0.302 to 3.04 per axle. The tridem axle load range was smaller compared to the observed ranges in single and tandem axle loads due to the small population from which the tridem axle load spectrum was derived (Class 13 and 19 vehicles only).

The potential range of urban local-industrial tridem axle loads is outlined in Table 6.3 and shown in Figure 6.5, and was generated using the minimum and maximum loads from the Chapter 4 load spectra. The tridem axle loads from the spectra ranged from a minimum of 4 kips to a maximum of 70 kips per tridem axle and correlated to AASHTO load equivalencies ranging from 0.0002 to 5.11 per tridem axle group on the freeway structure. This range corresponded to mean local-industrial tridem axle group load equivalencies ranging from 0.0002 to 4.55 per tridem axle group with a lower and upper range of 0.0001 to 18.2 per group.

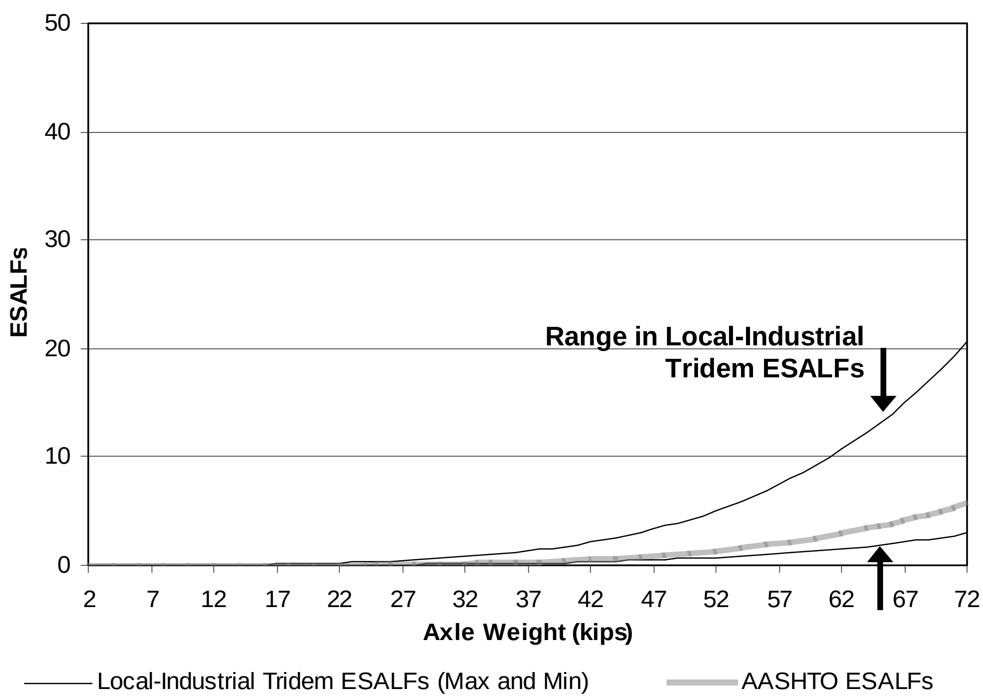


**Figure 6.5 - Local-Industrial Roadway Tridem Axle Group Urban ESALFs**

Table 6.3 –Local-Industrial Roadway Tridem Axle Group Urban ESALFs

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Local-Industrial ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 4 | 0.0002 | 0.0001 | 0.0002 | 0.0007 |
| 6 | 0.0007 | 0.0004 | 0.0006 | 0.0025 |
| 8 | 0.002 | 0.001 | 0.002 | 0.007 |
| 10 | 0.004 | 0.002 | 0.004 | 0.014 |
| 12 | 0.007 | 0.004 | 0.006 | 0.025 |
| 14 | 0.012 | 0.006 | 0.011 | 0.043 |
| 16 | 0.019 | 0.010 | 0.017 | 0.068 |
| 18 | 0.029 | 0.015 | 0.026 | 0.103 |
| 20 | 0.042 | 0.021 | 0.037 | 0.149 |
| 22 | 0.058 | 0.030 | 0.052 | 0.206 |
| 24 | 0.078 | 0.040 | 0.069 | 0.277 |
| 26 | 0.103 | 0.052 | 0.092 | 0.366 |
| 28 | 0.133 | 0.068 | 0.118 | 0.473 |
| 30 | 0.169 | 0.086 | 0.150 | 0.601 |
| 32 | 0.213 | 0.108 | 0.190 | 0.757 |
| 34 | 0.266 | 0.135 | 0.237 | 0.946 |
| 36 | 0.329 | 0.167 | 0.293 | 1.17 |
| 38 | 0.403 | 0.205 | 0.359 | 1.43 |
| 40 | 0.491 | 0.250 | 0.437 | 1.75 |
| **42** | **0.594** | **0.302** | **0.529** | **2.11** |
| **44** | **0.714** | **0.363** | **0.636** | **2.54** |
| **46** | **0.854** | **0.434** | **0.760** | **3.04** |
| 48 | 1.02 | 0.516 | 0.904 | 3.61 |
| 50 | 1.20 | 0.611 | 1.068 | 4.27 |
| 52 | 1.41 | 0.717 | 1.255 | 5.01 |
| 54 | 1.66 | 0.845 | 1.478 | 5.90 |
| 56 | 1.93 | 0.982 | 1.718 | 6.86 |
| 58 | 2.25 | 1.14 | 2.003 | 8.00 |
| 60 | 2.60 | 1.32 | 2.314 | 9.24 |
| 62 | 3.00 | 1.53 | 2.670 | 10.7 |
| 64 | 3.44 | 1.75 | 3.062 | 12.2 |
| 66 | 3.94 | 2.00 | 3.507 | 14.0 |
| 68 | 4.49 | 2.28 | 3.997 | 16.0 |
| 70 | 5.11 | 2.60 | 4.549 | 18.2 |
| 72 | 5.79 | 2.95 | 5.154 | 20.6 |
| 74 | 6.54 | 3.33 | 5.822 | 23.3 |
| 76 | 7.37 | 3.75 | 6.561 | 26.2 |
| 78 | 8.28 | 4.21 | 7.371 | 29.4 |
| 80 | 9.28 | 4.72 | 8.261 | 33.0 |
| 82 | 10.4 | 5.29 | 9.258 | 37.0 |
| 84 | 11.6 | 5.90 | 10.3 | 41.2 |
| 86 | 12.9 | 6.56 | 11.5 | 45.9 |
| 88 | 14.3 | 7.28 | 12.7 | 50.8 |
| 90 | 15.8 | 8.04 | 14.1 | 56.2 |

### 6.2 Arterial Roadway Urban ESALFs

The roadways measured for the urban arterial road type ranged in surface condition from poor (rough and containing numerous pavement patches) to good (smooth and recently refinished), as illustrated in Figures 6.6 and 6.7.

**Figure 6.6– 8th Street East (August 3, 2006), PSI Inc.**

**Figure 6.7– Avenue C (July 26, 2006), PSI Inc.**

As presented in Table 6.4 and Figure 6.8, the arterial road structures exhibited load equivalencies that were higher than those calculated for a typical AASHTO road with terminal serviceability of 2.5 and structural number of 2. This indicated that, as per the results of the non-destructive structural roadway testing performed throughout the City, urban arterial roadways generally performed worse than the freeway utilized for comparison.

The mean single axle loads across the seven vehicle configurations in the Chapter 4 load spectra ranged from 8 to 16 kips and correlated to AASHTO load equivalencies ranging from 0.047 to 0.613 per single axle group on the freeway structure, as highlighted in grey in Table 6.4. Based on the PSIPave SI results, the mean arterial single axle load equivalencies ranged from 0.086 to 1.12 per single axle, with upper and lower (±two SI ratio standard deviations) equivalencies ranging from 0.058 to 2.21 per axle.

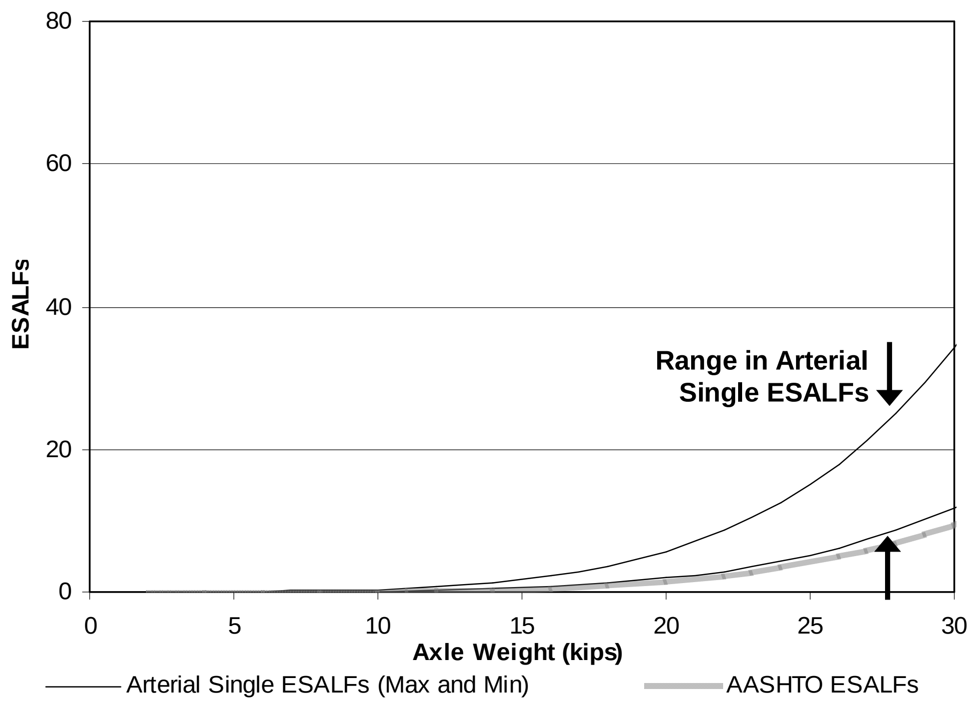


**Figure 6.8 - Arterial Roadway Single Axle Group Urban ESALFs**

The potential range of urban arterial single axle loads, outlined in Table 6.4 and Figure 6.8, was generated using the minimum and maximum loads from the Chapter 4 load spectra. The single axle loads in the spectra ranged from a minimum of 2 kips to a maximum of 28 kips per single axle, and correlated to AASHTO load equivalencies ranging from 0.0004 to 6.98 per single axle group on the freeway. This range corresponded to mean arterial single axle group load equivalencies ranging from 0.0007 to 12.8 per single axle group, with a lower and upper range of 0.0005 to 25.1 per group.

**Table 6.4 - Arterial Roadway Single Axle Group Urban ESALFs**

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Arterial ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0004 | 0.0005 | 0.0007 | 0.001 |
| 4 | 0.004 | 0.005 | 0.007 | 0.014 |
| 6 | 0.017 | 0.021 | 0.031 | 0.061 |
| **8** | **0.047** | **0.058** | **0.086** | **0.169** |
| **10** | **0.102** | **0.125** | **0.187** | **0.367** |
| **12** | **0.198** | **0.243** | **0.362** | **0.713** |
| **14** | **0.358** | **0.439** | **0.655** | **1.29** |
| **16** | **0.613** | **0.752** | **1.12** | **2.21** |
| 18 | 1.00 | 1.23 | 1.83 | 3.60 |
| 20 | 1.57 | 1.93 | 2.87 | 5.65 |
| 22 | 2.38 | 2.92 | 4.36 | 8.57 |
| 24 | 3.49 | 4.28 | 6.39 | 12.6 |
| 26 | 4.99 | 6.12 | 9.13 | 18.0 |
| 28 | 6.98 | 8.56 | 12.8 | 25.1 |
| 30 | 9.50 | 11.7 | 17.4 | 34.2 |
| 32 | 12.8 | 15.7 | 23.4 | 46.1 |
| 34 | 16.9 | 20.7 | 30.9 | 60.9 |
| 36 | 22.0 | 27.0 | 40.3 | 79.2 |
| 38 | 28.3 | 34.7 | 51.8 | 101.9 |
| 40 | 35.9 | 44.0 | 65.7 | 129.3 |
| 42 | 45.0 | 55.2 | 82.4 | 162.0 |
| 44 | 55.9 | 68.6 | 102.3 | 201.3 |
| 46 | 68.8 | 84.4 | 125.9 | 247.7 |
| 48 | 83.9 | 102.9 | 153.6 | 302.1 |
| 50 | 102.0 | 125.1 | 186.7 | 367.3 |

The upper bounds of the arterial roadway load equivalencies in Figure 6.8 represent the poorest roadway structural performance and exhibited an increase of 200 percent over the well-performing lower bounds. The range of arterial load equivalencies was much smaller than the range observed for the local-industrial load equivalencies, indicating more uniformity within arterial structural performances than the local-industrial structural performances. The maximum load equivalency factors for excellently performing arterial structures were 20 percent greater than the standard AASHTO load equivalencies. The poorly performing arterial road structures rendered load equivalencies that were approximately 260 percent greater than the AASHTO equivalencies.

Table 6.5 and Figure 6.9 illustrated the range of urban arterial tandem axle load equivalencies for the PSIPave SI ratios developed in Chapter 5. The mean tandem axle loads from the Chapter 4 load spectra ranged from 22 to 34 kips, and correlated to AASHTO load equivalencies ranging from 0.198 to 1.08 per tandem axle, as highlighted in Table 6.5. Based on the PSIPave SI results, the mean urban arterial tandem axle load equivalencies ranged from 0.362 to 1.98 per axle group, with upper and lower (±two SI ratio standard deviations) load equivalencies ranging from 0.243 to 3.89 per tandem axle group.

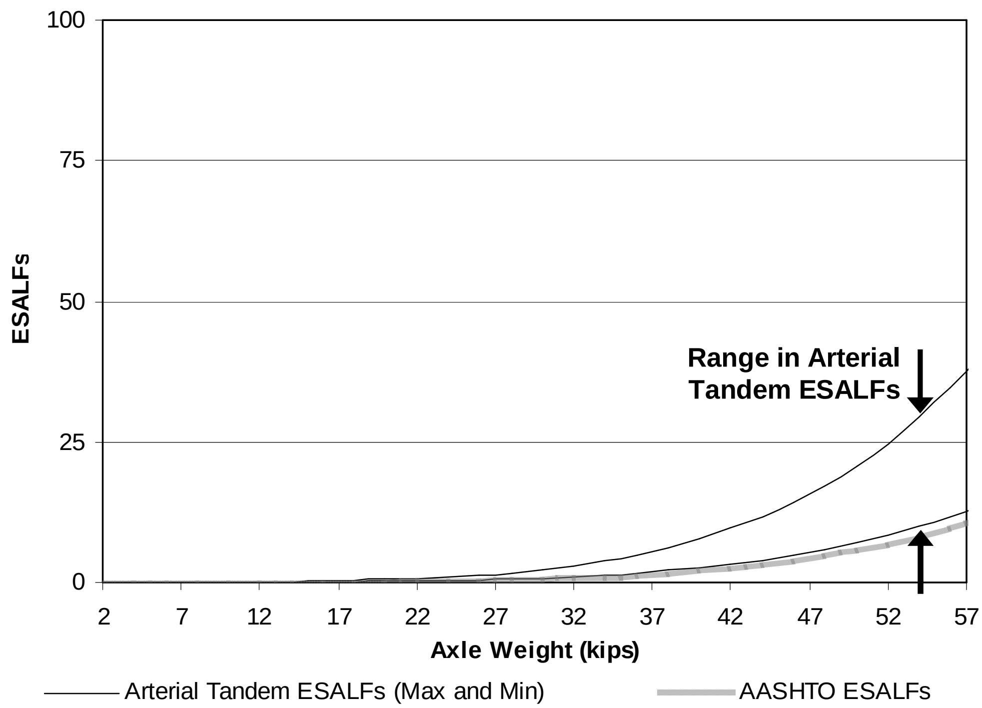


**Figure 6.9 - Arterial Roadway Tandem Axle Group Urban ESALFs**

The potential range of urban arterial tandem axle loads is outlined in Table 6.5 and Figure 6.9. The range was generated using the minimum and maximum tandem axle loads from the load spectra developed in Chapter 4. The tandem axle loads from the spectra ranged from a minimum of 2 kips to a maximum of 54 kips per axle group, and correlated to AASHTO load equivalencies ranging from 0.0001 to 8.14 per axle group on the freeway structure. This range corresponded to mean urban arterial tandem axle group load equivalencies ranging from 0.0002 to 14.9 per tandem axle group with a lower and upper range of 0.0001 to 29.3 per group.

**Table 6.5 - Arterial Roadway Tandem Axle Group Urban ESALFs**

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Arterial ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0001 | 0.0001 | 0.0002 | 0.0004 |
| 4 | 0.001 | 0.0006 | 0.0009 | 0.0018 |
| 6 | 0.002 | 0.002 | 0.004 | 0.007 |
| 8 | 0.006 | 0.007 | 0.011 | 0.022 |
| 10 | 0.013 | 0.016 | 0.024 | 0.047 |
| 12 | 0.024 | 0.029 | 0.044 | 0.086 |
| 14 | 0.041 | 0.050 | 0.075 | 0.148 |
| 16 | 0.065 | 0.080 | 0.119 | 0.234 |
| 18 | 0.097 | 0.119 | 0.178 | 0.349 |
| 20 | 0.141 | 0.173 | 0.258 | 0.508 |
| **22** | **0.198** | **0.243** | **0.362** | **0.713** |
| **24** | **0.273** | **0.335** | **0.500** | **0.983** |
| **26** | **0.370** | **0.454** | **0.677** | **1.33** |
| **28** | **0.493** | **0.605** | **0.902** | **1.78** |
| **30** | **0.648** | **0.795** | **1.19** | **2.33** |
| **32** | **0.843** | **1.03** | **1.54** | **3.04** |
| **34** | **1.08** | **1.33** | **1.98** | **3.89** |
| 36 | 1.38 | 1.69 | 2.53 | 4.97 |
| 38 | 1.73 | 2.12 | 3.17 | 6.23 |
| 40 | 2.16 | 2.65 | 3.95 | 7.78 |
| 42 | 2.67 | 3.28 | 4.89 | 9.61 |
| 44 | 3.27 | 4.01 | 5.98 | 11.8 |
| 46 | 3.98 | 4.88 | 7.28 | 14.3 |
| 48 | 4.80 | 5.89 | 8.78 | 17.3 |
| 50 | 5.76 | 7.07 | 10.5 | 20.7 |
| 52 | 6.87 | 8.43 | 12.6 | 24.7 |
| 54 | 8.14 | 9.99 | 14.9 | 29.3 |
| 56 | 9.60 | 11.8 | 17.6 | 34.6 |
| 58 | 11.3 | 13.9 | 20.7 | 40.7 |
| 60 | 13.1 | 16.1 | 24.0 | 47.2 |
| 62 | 15.3 | 18.8 | 28.0 | 55.1 |
| 64 | 17.6 | 21.6 | 32.2 | 63.4 |
| 66 | 20.3 | 24.9 | 37.2 | 73.1 |
| 68 | 23.3 | 28.6 | 42.6 | 83.9 |
| 70 | 26.6 | 32.6 | 48.7 | 95.8 |
| 72 | 30.3 | 37.2 | 55.5 | 109.1 |
| 74 | 34.4 | 42.2 | 63.0 | 123.9 |
| 76 | 38.9 | 47.7 | 71.2 | 140.1 |
| 78 | 43.9 | 53.9 | 80.3 | 158.1 |
| 80 | 49.4 | 60.6 | 90.4 | 177.9 |
| 82 | 55.4 | 68.0 | 101.4 | 199.5 |
| 84 | 61.9 | 75.9 | 113.3 | 222.9 |
| 86 | 69.1 | 84.8 | 126.5 | 248.8 |
| 88 | 76.9 | 94.3 | 140.7 | 276.9 |
| 90 | 85.4 | 104.8 | 156.3 | 307.5 |

Table 6.6 and Figure 6.10 illustrate the range of arterial tridem axle load equivalencies for the PSIPave SI ratios. The mean tridem axle load of the Chapter 4 load spectra ranged from 42 to 46 kips and correlated to AASHTO equivalencies from 0.594 to 0.854 per axle group, as highlighted in Table 6.6. The mean arterial tridem axle load equivalencies ranged from 0.899 to 1.31 per axle group, with upper and lower (±two SI ratio standard deviations) equivalencies of 0.602 to 2.57 per axle.

The potential range of arterial tridem axle loads is outlined in Table 6.6 and Figure 6.10, and was generated using the minimum and maximum axle loads from the Chapter 4 load spectra. The tridem loads from the spectra ranged from 4 kips to 70 kips, and correlated to AASHTO load equivalencies ranging from 0.0002 to 5.11 per axle on the freeway structure. This range corresponded to mean arterial tridem axle load equivalencies ranging from 0.0004 to 9.35 per axle with a lower and upper range of 0.0002 to 18.4 per axle group.

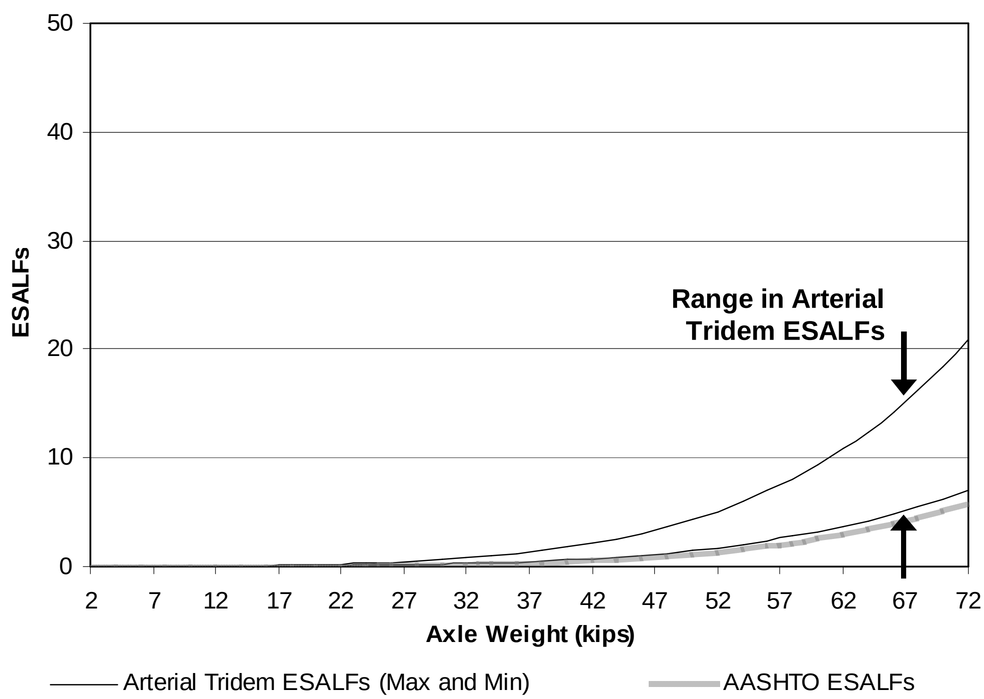


**Figure 6.10 - Arterial Roadway Tridem Axle Group Urban ESALFs**

**Table 6.6 - Arterial Roadway Tridem Axle Group Urban ESALFs**

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Arterial ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 4 | 0.0002 | 0.0002 | 0.0004 | 0.0007 |
| 6 | 0.0007 | 0.0009 | 0.0013 | 0.0025 |
| 8 | 0.002 | 0.002 | 0.004 | 0.007 |
| 10 | 0.004 | 0.005 | 0.007 | 0.014 |
| 12 | 0.007 | 0.009 | 0.013 | 0.025 |
| 14 | 0.012 | 0.015 | 0.022 | 0.043 |
| 16 | 0.019 | 0.023 | 0.035 | 0.068 |
| 18 | 0.029 | 0.036 | 0.053 | 0.104 |
| 20 | 0.042 | 0.052 | 0.077 | 0.151 |
| 22 | 0.058 | 0.071 | 0.106 | 0.209 |
| 24 | 0.078 | 0.096 | 0.143 | 0.281 |
| 26 | 0.103 | 0.126 | 0.189 | 0.371 |
| 28 | 0.133 | 0.163 | 0.243 | 0.479 |
| 30 | 0.169 | 0.207 | 0.309 | 0.609 |
| 32 | 0.213 | 0.261 | 0.390 | 0.767 |
| 34 | 0.266 | 0.326 | 0.487 | 0.958 |
| 36 | 0.329 | 0.404 | 0.602 | 1.18 |
| 38 | 0.403 | 0.494 | 0.738 | 1.45 |
| **40** | **0.491** | **0.602** | **0.899** | **1.77** |
| **42** | **0.594** | **0.729** | **1.09** | **2.14** |
| **44** | **0.714** | **0.876** | **1.31** | **2.57** |
| 46 | 0.854 | 1.05 | 1.56 | 3.08 |
| 48 | 1.02 | 1.25 | 1.86 | 3.65 |
| 50 | 1.20 | 1.47 | 2.20 | 4.32 |
| 52 | 1.41 | 1.73 | 2.58 | 5.08 |
| 54 | 1.66 | 2.04 | 3.04 | 5.98 |
| 56 | 1.93 | 2.37 | 3.53 | 6.95 |
| 58 | 2.25 | 2.76 | 4.12 | 8.10 |
| 60 | 2.60 | 3.19 | 4.76 | 9.36 |
| 62 | 3.00 | 3.68 | 5.49 | 10.8 |
| 64 | 3.44 | 4.22 | 6.30 | 12.4 |
| 66 | 3.94 | 4.83 | 7.21 | 14.2 |
| 68 | 4.49 | 5.51 | 8.22 | 16.2 |
| 70 | 5.11 | 6.27 | 9.35 | 18.4 |
| 72 | 5.79 | 7.10 | 10.6 | 20.8 |
| 74 | 6.54 | 8.02 | 12.0 | 23.5 |
| 76 | 7.37 | 9.04 | 13.5 | 26.5 |
| 78 | 8.28 | 10.2 | 15.2 | 29.8 |
| 80 | 9.28 | 11.4 | 17.0 | 33.4 |
| 82 | 10.4 | 12.8 | 19.0 | 37.4 |
| 84 | 11.6 | 14.2 | 21.2 | 41.8 |
| 86 | 12.9 | 15.8 | 23.6 | 46.4 |
| 88 | 14.3 | 17.5 | 26.2 | 51.5 |
| 90 | 15.8 | 19.4 | 28.9 | 56.9 |

## 6.3 Local and Collector Roadway Urban ESALFs

The roadways measured within the urban local and collector road category ranged in surface condition from moderate to good, as illustrated in Figures 6.11 and 6.12.

**Figure 6.11 – 31st Street (June 16, 2006), PSI Inc.**

**Figure 6.12 – Adelaide Street (June 13, 2006), PSI Inc.**

As presented in Table 6.7 and Figure 6.13, the local and collector roadways exhibited load equivalencies that were higher than those calculated for a typical AASHTO road with terminal serviceability of 2.5 and structural number of 2. This indicated that, as per the results of the non-destructive roadway testing performed throughout the City, urban local and collector roadways generally performed worse than the Circle Drive freeway utilized for comparison.

The mean single axle loads across the seven vehicle configurations in the Chapter 4 load spectra ranged from 8 to 16 kips and correlated to AASHTO load equivalencies ranging from 0.047 to 0.613 per single axle group on the freeway structure, as highlighted in grey in Table 6.7. The mean local and collector single axle PSIPave SI load equivalencies ranged from 0.177 to 2.30 per single axle, with upper and lower (±two SI ratio standard deviations) equivalencies ranging from 0.166 to 4.90 per single axle.

The potential range of urban local and collector single axle loads is outlined in Table 6.7 and Figure 6.13, and was generated using the minimum and maximum loads from the Chapter 4 load spectra. The single axle loads in the spectra ranged from a minimum of 2 kips to a maximum of 28 kips per single axle and correlated to AASHTO load equivalencies ranging from 0.0004 to 6.98 per single axle on the freeway structure. This range corresponded to mean local and collector single axle load equivalencies ranging from 0.0015 to 6.98 per single axle group, with a lower and upper range of 0.0010 to 55.8 per group.

**Table 6.7 – Local & Collector Roadway Single Axle Group Urban ESALFs**

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Local & Collector ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0004 | 0.0010 | 0.0015 | 0.0032 |
| 4 | 0.004 | 0.010 | 0.015 | 0.032 |
| 6 | 0.017 | 0.042 | 0.064 | 0.136 |
| **8** | **0.047** | **0.116** | **0.177** | **0.376** |
| **10** | **0.102** | **0.251** | **0.383** | **0.815** |
| **12** | **0.198** | **0.487** | **0.744** | **1.58** |
| **14** | **0.358** | **0.880** | **1.35** | **2.86** |
| **16** | **0.613** | **1.51** | **2.30** | **4.90** |
| 18 | 1.00 | 2.46 | 3.76 | 7.99 |
| 20 | 1.57 | 3.86 | 5.90 | 12.5 |
| 22 | 2.38 | 5.85 | 8.95 | 19.0 |
| 24 | 3.49 | 8.58 | 13.1 | 27.9 |
| 26 | 4.99 | 12.3 | 18.8 | 39.9 |
| 28 | 6.98 | 17.2 | 26.2 | 55.8 |
| 30 | 9.50 | 23.4 | 35.7 | 75.9 |
| 32 | 12.8 | 31.5 | 48.1 | 102.3 |
| 34 | 16.9 | 41.5 | 63.5 | 135.0 |
| 36 | 22.0 | 54.1 | 82.7 | 175.8 |
| 38 | 28.3 | 69.6 | 106.4 | 226.1 |
| 40 | 35.9 | 88.3 | 135.0 | 286.8 |
| 42 | 45.0 | 110.6 | 169.2 | 359.5 |
| 44 | 55.9 | 137.4 | 210.2 | 446.6 |
| 46 | 68.8 | 169.1 | 258.7 | 549.7 |
| 48 | 83.9 | 206.2 | 315.4 | 670.3 |
| 50 | 102.0 | 250.7 | 383.5 | 815.0 |

The upper bounds of the local and collector roadway load equivalencies in Figure 6.13 represent the poorest roadway structural performance and exhibited an increase of 225 percent over the excellently-performing lower bounds. The range of local and collector load equivalencies was much smaller than the range observed for the local-industrial load equivalencies, indicating more uniformity within local and collector roadway structural performances than the local-industrial structural performances. The maximum load equivalency factors for excellently performing local and collector structures were 150 percent greater than the standard AASHTO load equivalencies. The poorly performing road structures rendered load equivalencies that were 700 percent greater than AASHTO equivalencies.

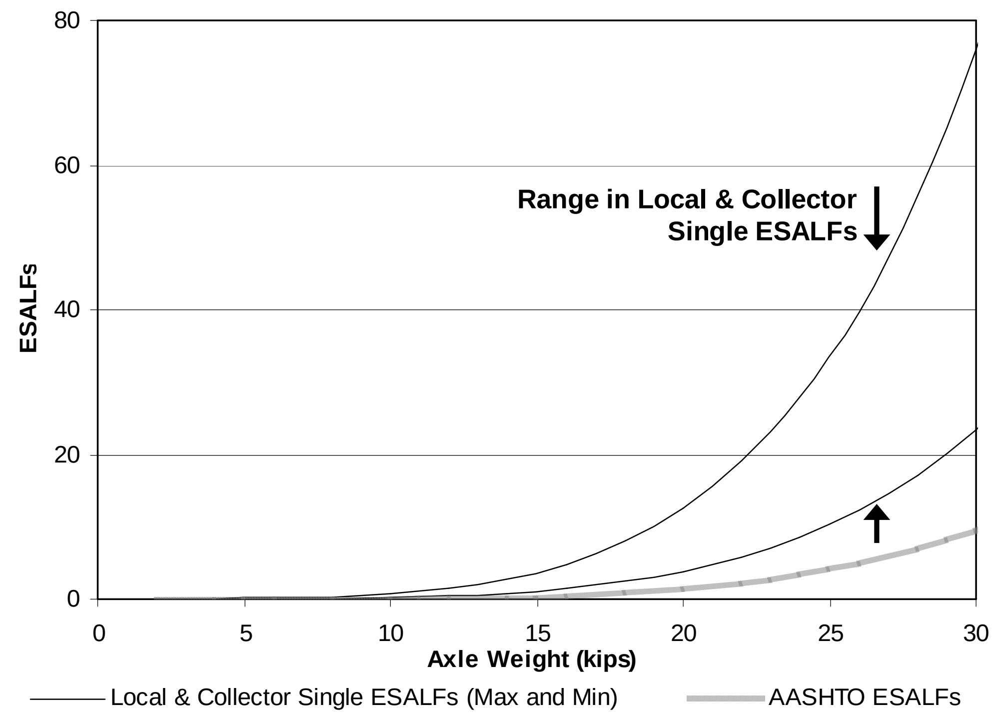


**Figure 6.13 – Local & Collector Roadway Single Axle Group Urban ESALFs**

Figure 6.14 and Table 6.8 illustrate the range in local and collector tandem axle group load equivalencies for the PSIPave SI ratios developed in Chapter 5. The mean tandem axle loads from the Chapter 4 load spectra ranged from 22 to 34 kips and correlated to AASHTO load equivalencies ranging from 0.198 to 1.08 per tandem axle, as highlighted in Table 6.8. Based on the PSIPave SI results, the mean urban local and collector tandem axle load equivalencies ranged from 0.744 to 4.06 per tandem axle, with upper and lower load equivalencies (±two SI ratio standard deviations) from 0.487 to 8.63 per axle.

The potential range of urban local and collector tandem axle loads is outlined in Table 6.8 and Figure 6.14, and was generated using the minimum and maximum loads from the Chapter 4 load spectra. The tandem axle loads in the spectra ranged from a minimum of 2 kips to a maximum of 54 kips per tandem axle and correlated to AASHTO load equivalencies ranging from 0.0001 to 8.14 per tandem axle. This range corresponded to mean local and collector tandem axle group load equivalencies ranging from 0.0004 to 30.6 per axle, with a lower and upper range of 0.0002 to 65.0 per group.

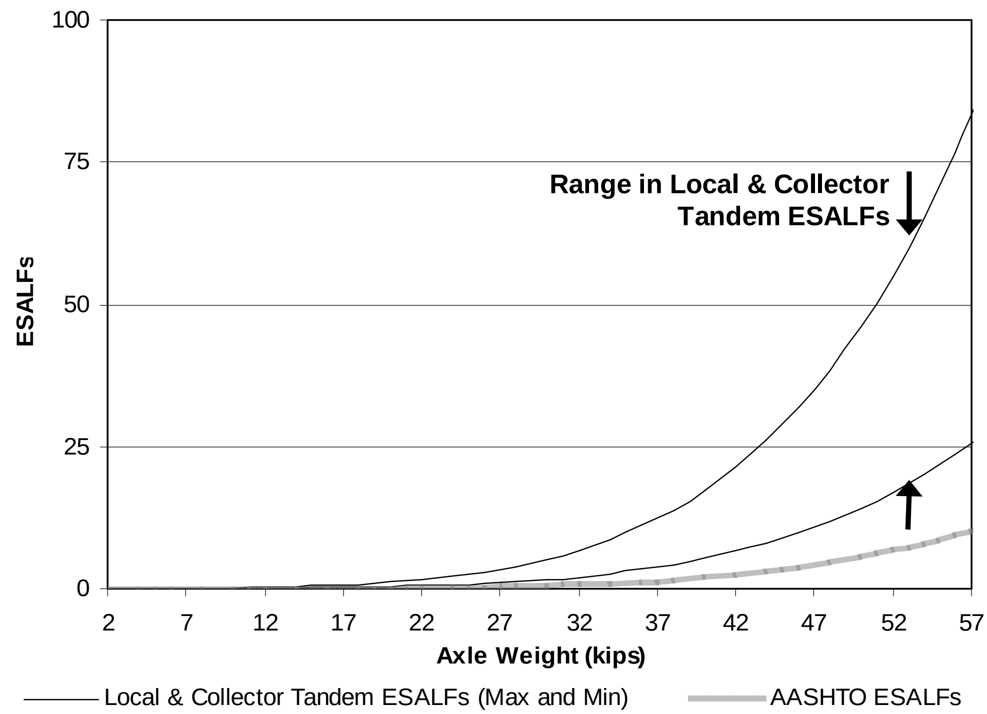


**Figure 6.14 – Local & Collector Roadway Tandem Axle Group Urban ESALFs**

**Table 6.8 – Local & Collector Roadway Tandem Axle Group Urban ESALFs**

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Local & Collector ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0001 | 0.0002 | 0.0004 | 0.0008 |
| 4 | 0.001 | 0.0012 | 0.0019 | 0.0040 |
| 6 | 0.002 | 0.005 | 0.008 | 0.016 |
| 8 | 0.006 | 0.015 | 0.023 | 0.048 |
| 10 | 0.013 | 0.032 | 0.049 | 0.104 |
| 12 | 0.024 | 0.059 | 0.090 | 0.192 |
| 14 | 0.041 | 0.101 | 0.154 | 0.328 |
| 16 | 0.065 | 0.160 | 0.244 | 0.519 |
| 18 | 0.097 | 0.238 | 0.365 | 0.775 |
| 20 | 0.141 | 0.347 | 0.530 | 1.13 |
| **22** | **0.198** | **0.487** | **0.744** | **1.58** |
| **24** | **0.273** | **0.671** | **1.03** | **2.18** |
| **26** | **0.370** | **0.910** | **1.39** | **2.96** |
| **28** | **0.493** | **1.21** | **1.85** | **3.94** |
| **30** | **0.648** | **1.59** | **2.44** | **5.18** |
| **32** | **0.843** | **2.07** | **3.17** | **6.74** |
| **34** | **1.08** | **2.65** | **4.06** | **8.63** |
| 36 | 1.38 | 3.39 | 5.19 | 11.0 |
| 38 | 1.73 | 4.25 | 6.50 | 13.8 |
| 40 | 2.16 | 5.31 | 8.12 | 17.3 |
| 42 | 2.67 | 6.56 | 10.0 | 21.3 |
| 44 | 3.27 | 8.04 | 12.3 | 26.1 |
| 46 | 3.98 | 9.78 | 15.0 | 31.8 |
| 48 | 4.80 | 11.8 | 18.0 | 38.4 |
| 50 | 5.76 | 14.2 | 21.7 | 46.0 |
| 52 | 6.87 | 16.9 | 25.8 | 54.9 |
| 54 | 8.14 | 20.0 | 30.6 | 65.0 |
| 56 | 9.60 | 23.6 | 36.1 | 76.7 |
| 58 | 11.3 | 27.8 | 42.5 | 90.3 |
| 60 | 13.1 | 32.2 | 49.3 | 104.7 |
| 62 | 15.3 | 37.6 | 57.5 | 122.2 |
| 64 | 17.6 | 43.3 | 66.2 | 140.6 |
| 66 | 20.3 | 49.9 | 76.3 | 162.2 |
| 68 | 23.3 | 57.3 | 87.6 | 186.2 |
| 70 | 26.6 | 65.4 | 100.0 | 212.5 |
| 72 | 30.3 | 74.5 | 113.9 | 242.1 |
| 74 | 34.4 | 84.6 | 129.3 | 274.8 |
| 76 | 38.9 | 95.6 | 146.3 | 310.8 |
| 78 | 43.9 | 107.9 | 165.1 | 350.8 |
| 80 | 49.4 | 121.4 | 185.7 | 394.7 |
| 82 | 55.4 | 136.2 | 208.3 | 442.6 |
| 84 | 61.9 | 152.2 | 232.7 | 494.6 |
| 86 | 69.1 | 169.9 | 259.8 | 552.1 |
| 88 | 76.9 | 189.0 | 289.1 | 614.4 |
| 90 | 85.4 | 209.9 | 321.1 | 682.3 |

Table 6.9 and Figure 6.15 illustrate the range in local and collector PSIPave SI tridem axle load equivalencies. The mean tridem axle loads from the Chapter 4 load spectra ranged from 42 to 46 kips and correlated to AASHTO load equivalencies ranging from 0.59 to 0.85 per tridem axle, as highlighted in Table 6.9. Based on the PSIPave SI results, the mean local and collector tridem axle load equivalencies ranged from 2.23 to 3.21 per axle, with upper and lower (±two SI ratio standard deviations) equivalencies ranging from 1.46 to 6.82 per tridem axle.

The potential range of local and collector tridem axle loads is outlined in Table 6.9 and Figure 6.15, and was generated using the minimum and maximum loads from the Chapter 4 spectra. The tridem axle loads in the spectra ranged from 4 kips to 70 kips per tridem axle and correlated to AASHTO equivalencies ranging from 0.0002 to 5.11 per tridem group on the freeway structure. This range corresponded to local and collector tridem axle load equivalencies ranging from 0.0008 to 19.2 per axle, with a lower and upper range of 0.0005 to 40.8 per axle.

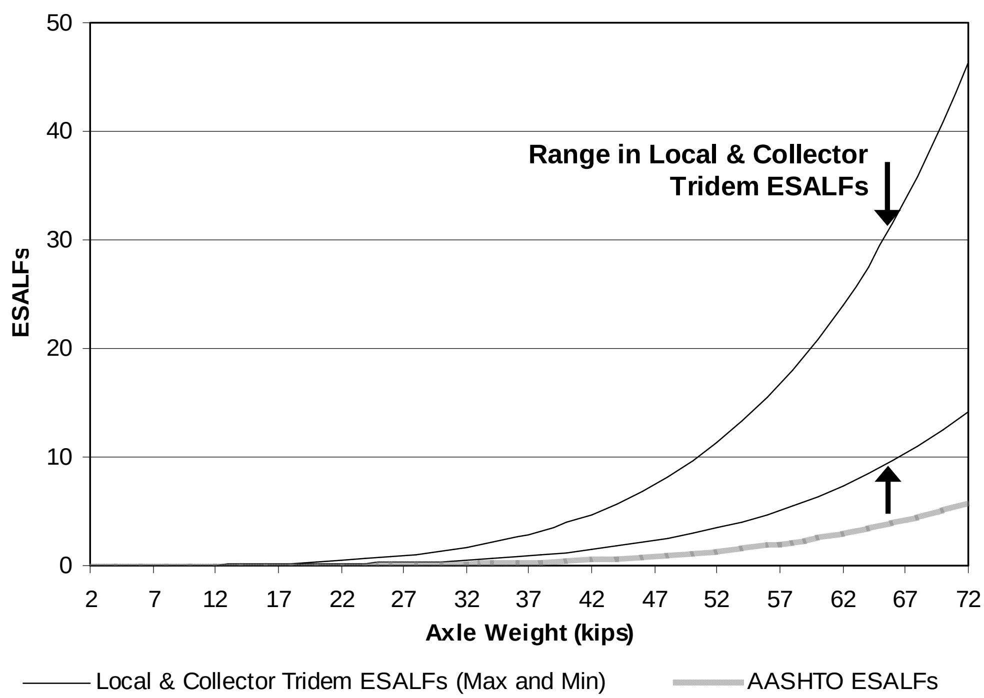


**Figure 6.15 – Local & Collector Roadway Tridem Axle Group Urban ESALFs**

Table 6.9 – Local & Collector Roadway Tridem Axle Group Urban ESALFs

| Axle Weight (kips) | AASHTO ESALF | Lower ESALF Range | Mean Local & Collector ESALF | Upper ESALF Range |
|---|---|---|---|---|
| 2 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 4 | 0.0002 | 0.0005 | 0.0008 | 0.0016 |
| 6 | 0.0007 | 0.0017 | 0.0026 | 0.0056 |
| 8 | 0.002 | 0.005 | 0.008 | 0.016 |
| 10 | 0.004 | 0.010 | 0.015 | 0.032 |
| 12 | 0.007 | 0.017 | 0.026 | 0.056 |
| 14 | 0.012 | 0.029 | 0.045 | 0.096 |
| 16 | 0.019 | 0.047 | 0.071 | 0.152 |
| 18 | 0.029 | 0.071 | 0.109 | 0.232 |
| 20 | 0.042 | 0.103 | 0.158 | 0.336 |
| 22 | 0.058 | 0.143 | 0.218 | 0.463 |
| 24 | 0.078 | 0.192 | 0.293 | 0.623 |
| 26 | 0.103 | 0.253 | 0.387 | 0.823 |
| 28 | 0.133 | 0.327 | 0.500 | 1.06 |
| 30 | 0.169 | 0.415 | 0.635 | 1.35 |
| 32 | 0.213 | 0.524 | 0.801 | 1.70 |
| 34 | 0.266 | 0.654 | 1.00 | 2.13 |
| 36 | 0.329 | 0.809 | 1.24 | 2.63 |
| 38 | 0.403 | 0.991 | 1.52 | 3.22 |
| 40 | 0.491 | 1.21 | 1.85 | 3.92 |
| **42** | **0.594** | **1.46** | **2.23** | **4.75** |
| **44** | **0.714** | **1.76** | **2.68** | **5.70** |
| **46** | **0.854** | **2.10** | **3.21** | **6.82** |
| 48 | 1.02 | 2.50 | 3.82 | 8.11 |
| 50 | 1.20 | 2.95 | 4.51 | 9.59 |
| 52 | 1.41 | 3.47 | 5.30 | 11.3 |
| 54 | 1.66 | 4.08 | 6.24 | 13.3 |
| 56 | 1.93 | 4.74 | 7.26 | 15.4 |
| 58 | 2.25 | 5.53 | 8.46 | 18.0 |
| 60 | 2.60 | 6.39 | 9.78 | 20.8 |
| 62 | 3.00 | 7.37 | 11.3 | 24.0 |
| 64 | 3.44 | 8.46 | 12.9 | 27.5 |
| 66 | 3.94 | 9.69 | 14.8 | 31.5 |
| 68 | 4.49 | 11.0 | 16.9 | 35.9 |
| 70 | 5.11 | 12.6 | 19.2 | 40.8 |
| 72 | 5.79 | 14.2 | 21.8 | 46.3 |
| 74 | 6.54 | 16.1 | 24.6 | 52.3 |
| 76 | 7.37 | 18.1 | 27.7 | 58.9 |
| 78 | 8.28 | 20.4 | 31.1 | 66.2 |
| 80 | 9.28 | 22.8 | 34.9 | 74.1 |
| 82 | 10.4 | 25.6 | 39.1 | 83.1 |
| 84 | 11.6 | 28.5 | 43.6 | 92.7 |
| 86 | 12.9 | 31.7 | 48.5 | 103.1 |
| 88 | 14.3 | 35.2 | 53.8 | 114.3 |
| 90 | 15.8 | 38.8 | 59.4 | 126.2 |

### 6.4 Application of Urban ESALFs for Design

The hybrid bus illustrated in Figure 6.16 is typical of the low floor transit vehicle configurations currently utilized by the City of Saskatoon Transit Services Department.


**Figure 6.16 – City of Saskatoon Hybrid Transit Bus**

The bus configuration featured in Figure 6.16 consists of single axles located at both the front and rear of the vehicle. The front Gross Axle Weight Rating (GAWR) for this vehicle is 6,700 kg and the rear GAWR is 13,000 kg, for a total Gross Vehicle Weight Rating (GVWR) of 19,700 kg. The Equivalent Single Axle Load of this vehicle, calculated assuming operational weights equivalent to the GAWR, are illustrated by urban road type in Figure 6.17.

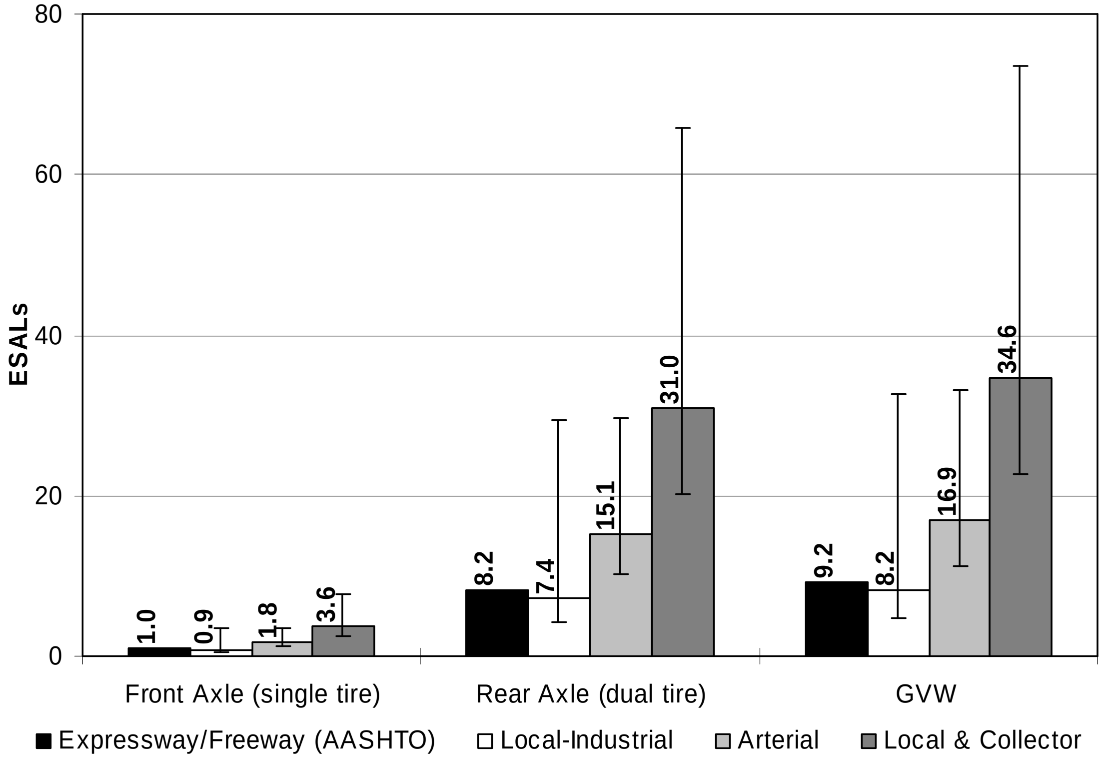


**Figure 6.17 – City of Saskatoon Hybrid Transit Bus Loads by Urban Road Type**

As illustrated in Figure 6.17, the model transit vehicle configuration generated a load of 9.2 ESALs as per the standard AASHTO equivalencies for a typical urban freeway outlined in Chapter 5. Utilizing the mean PSIPave SI ratios developed in Chapter 5, the mean equivalent load generated by the model transit vehicle was 8.2 ESALs on urban local-industrial roadways, 16.9 ESALs on urban arterial roadways and 34.6 ESALs on urban collector and local roadways. The potential loading from this vehicle (mean SI ratio ±two SI ratio standard deviations) ranged from 5 to 33 ESALs on local-industrial roadways, from 11 to 33 ESALs on arterial roadways, and from 23 to 74 ESALs on urban local and collector roadways. Given that the majority of transit travel is typically conducted on arterial, collector and local roadways, it is evident that transit operations may have incredibly deleterious effects on urban roadways. As such, it is imperative that consideration for roadway condition and maintenance be considered when generating or maintaining routes requiring repeated loading from heavy traffic.

### 6.5 Summary of Urban ESALFs for Design

The mechanistic-empirical urban load equivalencies presented in this chapter were formulated utilizing the range of PSIPave Structural Index ratios obtained from the 2006 City of Saskatoon Asset Management Pilot Study. The resulting urban load equivalencies were presented alongside their conventional AASHTO load equivalency factors to highlight the varying magnitudes of differentiation between the ESALFs for each urban road class and the conventional AASHTO load equivalencies representing an urban freeway (a.k.a. Circle Drive).

The local-industrial road class exhibited the largest range in load equivalency factors, with a total difference of 600 percent between the upper and lower bounds (± two standard deviations from the mean PSIPave SI). The large range for this road type indicated that there may be little uniformity amongst road structures and materials as compared to the other urban roadways. The conventional AASHTO equivalencies were slightly larger than the average local-industrial roadway equivalencies. However, the local-industrial roadways tested in the City of Saskatoon Asset Management study had all been recently rebuilt and/or received base strengthening. As such, it was concluded that the typical local-industrial roadway within the City would exhibit load equivalencies that were higher than those gathered in this study, generating an anticipated range of equivalency factors between those obtained on urban freeways and expressways, and those from major urban arterials. The results of the local-industrial roadway study showed that urban local-industrial ESALFs could range from 50 percent less than the conventional AASHTO equivalencies on well performing roadways to 250 percent greater than conventional AASHTO equivalencies on poorly-performing roadways.

The urban arterial road class exhibited a 200 percent range in ESALFs between the upper and lower bounds of the PSIPave SI ratio equivalencies. Compared to the range observed for local-industrial roadways, the difference between the upper and lower equivalencies for arterials indicated that there was much more uniformity amongst pavement structure and roadway materials in this road class. The results of the arterial study showed that ESALFs ranged from 20 percent to 260 percent greater than the conventional AASHTO equivalencies. The upper range of load equivalencies for the arterial road class was equivalent to the upper range for the local-industrial road class, leading to the conclusion that some of the local-industrial roads tested in the study had either similar structures or similar material properties. It was also concluded that a larger test group of local-industrial roadways would produce high load equivalencies that would range between arterial and freeway/expressway equivalencies.

The urban local and collector road class exhibited a 225 percent range in ESALFs between the upper and lower bounds of the PSIPave SI ratio equivalencies. Similar to the range observed for arterial roadways, the difference between the upper and lower equivalencies of the local and collector roadways indicated that there was more uniformity amongst pavement structure and roadways materials for this road class than for the local-industrial road class. The results of the study showed that urban ESALFs for urban local and collector roadways ranged from 150 to 700 percent greater than conventional AASHTO equivalencies. The greater upper equivalency bound for this road class indicated that local and collector roadways were exceptionally sensitive to the heavy loads created by large vehicles. As such, it was concluded that repeated utilization of this road class by commercial vehicles would radically reduce the lifespan of the City's local and collector roadway infrastructure.

# CHAPTER 7 - SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Equivalent Single Axle Loads (ESALs) have been the standard traffic loading measure used in highway engineering and pavement management practices for decades. ESALs were designed in the late 1950's by AASHO and facilitated uniform user-friendly pavement design calculations that did not require the accumulation of different damage rates for specific distress types (Lu and Harvey 2006). Given the sensitivity of typical road materials to shear stresses and loading rates, combined with the reduced traffic speeds, increased stop and go conditions, and channelized haul corridors in urban jurisdictions, the damage inflicted by commercial vehicles on urban roadways can be much more drastic than in a rural environment (Berthelot et al. 1999). As such, there are several significant limitations to the application of conventional ESALs for use in the engineering and management of urban roadways subjected to modern traffic loads.

Due to the limitations of conventional load equivalency calculations when applied to urban pavements, the objective of this research was to collect urban traffic load spectra to investigate the formulation of urban load equivalencies across different urban road types. Since roadway damage can be related to pavement deflection and deformation caused by loads (AASHTO 1993), structural testing data from freeways and expressways (representative of a typical highway structure) were used as a baseline to assess various urban road structures in terms of a typical AASHTO roadway. The load spectra obtained from the Circle/Preston VWIM freeway site was applied to the structural testing ratios in order to generate urban load equivalency factors based on the AASHTO load spectra. As such, this research hypothesized that WIM was a viable technology for providing reliable traffic data for agency analysis and that

WIM technology could be applied to generate mechanistic-empirical load equivalencies for urban roadway structures.

## 7.1 Traffic Load Spectra

A traffic load spectra data was collected using a VWIM system located on Circle Drive east of the Circle Drive Bridge. The VWIM system was calibrated and the post-calibration operations were validated in order to confirm reliability of the traffic load spectra data. The WIM system error was observed to shift over time during the process of VWIM calibration and system validation. As such, a daily error factor was interpolated for the traffic load spectra data under the assumption that the shifting was a linear event.

A detailed traffic load spectra was collected over seven consecutive days at the Circle/Preston VWIM site. Analysis of the data indicated that 97 percent of the observed trucks consisted of:

- Two and three axle straight trucks and straight trucks with tandem steering;
- Four, five and six axle tractor semi-trailer units, and;
- Eight axle B-trains.

Assessment of the cumulative loads by vehicle class indicated that the majority of the recorded ESALs were contributed by five axle semi-trailer units and eight axle B-trains, followed by three axle straight trucks and six axle semi-trailer units. The overloading trends observed within the traffic load spectra implied that the eight axle B-trains presented the most overweight records of any of the vehicle classes, followed by five axle semi trailers and three axle straight trucks.

Given the results of the calibration and reliability validation analysis, WIM technology provided a suitable platform for the generation of the traffic load spectra on Circle Drive with results that appeared to be intuitive with general commodity trends and loading patterns.

## 7.2 Roadway Primary Mechanistic Response Relationships

In 2006, the City of Saskatoon completed a comprehensive roadway structural assessment across City streets. GPR and HWD were utilized to assess the structural composition and load responses of pavements when submitted to heavy truck loadings (PSI 2007). Several measures of roadway deflection and primary pavement responses were combined to create PSIPave Structural Indexes reflective of the pavement responses to loading on various urban road classes.

The range of SI ratings for the various urban road types were assessed using a method of ratio comparison with the mean PSIPave SI from Circle Drive near the VWIM site as a baseline. Ratio comparison with Circle Drive as a baseline allowed for the generation of a range of load equivalency factors (mean and mean ± two standard deviations) tailored specifically to the primary responses of the local-industrial, arterial, and local and collector urban pavements.

## 7.3 Mechanistic-Empirical Urban ESALFs

The objective of this research was to investigate a framework for calculating load equivalency factors across different urban roadways. Mechanistic-empirical urban load equivalency tables for single, tandem and tridem axle groups were formulated utilizing the range of PSIPave Structural Index ratio factors for each urban road class. The resulting urban load equivalencies were presented alongside their conventional AASHTO ESALF counterparts to highlight the varying magnitudes of differentiation between the ESALFs for each urban road class.

The mean urban local-industrial roadway load equivalencies were smaller than the conventional AASHTO load equivalencies. However, due to the limited selection of local-industrial roadways for testing, it was concluded that the typical local-industrial roadway within City limits would actually exhibit load equivalency factors that were higher than those obtained in this study. Despite the skewed test population, the results of this study demonstrated that mechanistic-empirical urban ESALFs for local-industrial roadways could range from 50 percent less than the conventional AASHTO equivalencies to 250 percent greater than conventional AASHTO ESALs.

The urban ESALFs for arterial roadways ranged from 20 percent to 260 percent greater than the conventional AASHTO equivalencies. Urban ESALFs for local and collector roadways ranged from 150 to 700 percent greater than the conventional AASHTO equivalencies. The large upper equivalencies for the local and collector roads indicated that this road class was exceptionally sensitive to heavier loads and that repeated commercial traffic patterns on this type of urban road would most likely reduce the lifespan of the City's local and collector roadway infrastructure.

### 7.4 Study Conclusions and Recommendations for Future Research

This research was driven by the concept that AASHTO equivalent single axle load calculations were not reflective of the damage incurred by roadways under urban-specific loading conditions. The need for traffic load spectra monitoring was emphasized in light of the inherent lack of understanding of commercial vehicle operations within urban jurisdictions. This research verified that understanding the structural capabilities of urban roadway infrastructure and the traffic load spectra to which it is exposed is crucial for successful urban roadway asset management. As such, this research showed that WIM, in conjunction with non-destructive structural testing, were viable technologies for the generation of location-specific traffic load spectra for the purpose of establishing mechanistic-empirical urban ESAL tables.

The upper range of the urban arterial load equivalencies was similar to the upper range of the local-industrial load equivalencies, indicating that the local-industrial roads could have structures and/or material properties that were similar to those of the urban arterials. Due to the nature of the test group representing the local-industrial roadways, it was concluded that a larger test group would most likely produce mean results with lower structural indices than those obtained within this study.

In light of the results of this research, it is recommended that further non-destructive structural testing be completed on a greater sample of various urban road types within the City to generate a representative cross-section of the typical structural classes. The testing samples should be selected so as to embody the actual operational status of a variety of roadways within the urban infrastructure, including roadways that have recently been rehabilitated and those requiring repair. It is further recommended that individual WIM systems are located strategically throughout the City with seasonal data collection cycles. Due to its location on a main urban corridor, the Circle/Preston VWIM site would capture a large portion of the vehicles traveling within the City for various pick-up, delivery and service purposes. Therefore, the Circle/Preston VWIM would generate suitable approximations of the potential axle group load spectra for various types of urban roadways. However, other locations, such as commercial corridors, should be considered for monitoring to generate a more accurate assessment of the internal urban traffic patterns which may be overlooked due to routing decisions bypassing Circle Drive.

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## APPENDIX A - VWIM SYSTEM CALIBRATION RESULTS

**Table A.1 - Westbound Curb Lane Calibration Results**

| Test | Steering Axle | | Drive Axle | | Trailer Axle | | GVW | |
|---|---|---|---|---|---|---|---|---|
| | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. |
| **1** | -350 | -7.10 | 167 | 1.03 | -1,295 | -6.49 | -1,478 | -3.60 |
| **2** | -2 | -0.04 | 901 | 5.55 | 281 | 1.41 | 1,180 | 2.87 |
| **3** | 322 | 6.53 | -395 | -2.43 | -2,055 | -10.30 | -2,128 | -5.18 |
| **4** | 234 | 4.75 | 261 | 1.61 | -2,111 | -10.58 | -1,616 | -3.93 |
| **5** | 128 | 2.60 | 237 | 1.46 | -479 | -2.40 | -114 | -0.28 |
| **6** | 180 | 3.65 | 493 | 3.04 | 319 | 1.60 | 992 | 2.41 |
| **7** | 56 | 1.14 | -491 | -3.03 | -3,263 | -16.35 | -3,698 | -9.00 |
| **8** | 376 | 7.63 | -299 | -1.84 | 67 | 0.34 | 144 | 0.35 |
| **9** | 254 | 5.15 | -515 | -3.17 | -129 | -0.65 | -390 | -0.95 |
| **10** | 356 | 7.22 | -103 | -0.63 | -1,081 | -5.42 | -828 | -2.01 |
| **Mean** | **155** | **3.15** | **26** | **0.16** | **-975** | **-4.88** | **-794** | **-1.93** |
| **St. Dev.** | **217** | **4.4** | **467** | **2.88** | **1,207** | **6.05** | **1,489** | **3.62** |
| **CV** | **140%** | **140%** | **1,796%** | **1,800%** | **-124%** | **-124%** | **-188%** | **-188%** |

**Table A.2 - Westbound Median Lane Calibration Results**

| Test | Steering | | Drive | | Trailer | | GVW | |
|---|---|---|---|---|---|---|---|---|
| | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. |
| 1 | -270 | -5.48 | -582 | -3.59 | 805 | 4.03 | -47 | -0.11 |
| 2 | 184 | 3.73 | -366 | -2.26 | 62 | 0.31 | -120 | -0.29 |
| 3 | -334 | -6.77 | -1,027 | -6.33 | -950 | -4.76 | -2,311 | -5.62 |
| 4 | -77 | -1.56 | -19 | -0.12 | 1,745 | 8.74 | 1,649 | 4.01 |
| 5 | 179 | 3.63 | -370 | -2.28 | -903 | -4.53 | -1,094 | -2.66 |
| 6 | 0 | 0.00 | -523 | -3.22 | -449 | -2.25 | -972 | -2.36 |
| 7 | 157 | 3.18 | -265 | -1.63 | -402 | -2.01 | -510 | -1.24 |
| 8 | 254 | 5.15 | -244 | -1.50 | 477 | 2.39 | 487 | 1.18 |
| 9 | -55 | -1.12 | 194 | 1.20 | 633 | 3.17 | 772 | 1.88 |
| 10 | -35 | -0.71 | 162 | 1.00 | 640 | 3.21 | 767 | 1.87 |
| **Avg.** | **0** | **0.01** | **-304** | **-1.87** | **166** | **0.83** | **-138** | **-0.34** |
| **St. Dev.** | **197** | **4** | **366** | **2.26** | **853** | **4.27** | **1,141** | **2.77** |
| **CV** | **0%** | **0%** | **-120%** | **-120%** | **514%** | **514%** | **-827%** | **-827%** |

**Table A.3 - Eastbound Curb Lane Calibration Results**

| Test | Steering | | Drive | | Trailer | | GVW | |
|---|---|---|---|---|---|---|---|---|
| | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. |
| 1 | 86 | 1.74 | 31 | 0.19 | 793 | 3.97 | 910 | 2.21 |
| 2 | 396 | 8.03 | -853 | -5.26 | 39 | 0.20 | -418 | -1.02 |
| 3 | 806 | 16.35 | 1,283 | 7.91 | 341 | 1.71 | 2,430 | 5.91 |
| 4 | 562 | 11.40 | -247 | -1.52 | 117 | 0.59 | 432 | 1.05 |
| 5 | -114 | -2.31 | -401 | -2.47 | -1,803 | -9.04 | -2,318 | -5.64 |
| 6 | 822 | 16.67 | 129 | 0.80 | 235 | 1.18 | 1,186 | 2.88 |
| 7 | 298 | 6.04 | -441 | -2.72 | -1,667 | -8.35 | -1,810 | -4.40 |
| 8 | 406 | 8.24 | 75 | 0.46 | -2,187 | -10.96 | -1,706 | -4.15 |
| 9 | 364 | 7.38 | -623 | -3.84 | -2,599 | -13.02 | -2,858 | -6.95 |
| 10 | 254 | 5.15 | -925 | -5.70 | -847 | -4.24 | -1,518 | -3.69 |
| **Avg.** | **388** | **7.87** | **-197** | **-1.22** | **-758** | **-3.80** | **-567** | **-1.38** |
| **St. Dev.** | **291** | **5.91** | **638** | **3.93** | **1,218** | **6.11** | **1,742** | **4.24** |
| **CV** | **75%** | **75%** | **-324%** | **-324%** | **-161%** | **-161%** | **-307%** | **-307%** |

**Table A.4 - Eastbound Median Lane Calibration Results**

| Test | Steering | | Drive | | Trailer | | GVW | |
|---|---|---|---|---|---|---|---|---|
| | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. | Diff. (kg) | % Diff. |
| 1 | 422 | 8.56 | -541 | -3.33 | 1,110 | 5.56 | 991 | 2.41 |
| 2 | 244 | 4.95 | -219 | -1.35 | 739 | 3.70 | 764 | 1.86 |
| 3 | 369 | 7.48 | 212 | 1.31 | 54 | 0.27 | 635 | 1.54 |
| 4 | 42 | 0.85 | -299 | -1.84 | 2,143 | 10.74 | 1,886 | 4.59 |
| 5 | 106 | 2.15 | -295 | -1.82 | -46 | -0.23 | -235 | -0.57 |
| 6 | 7 | 0.14 | -500 | -3.08 | 536 | 2.69 | 43 | 0.10 |
| 7 | -256 | -5.19 | -214 | -1.32 | -1,137 | -5.70 | -1,607 | -3.91 |
| 8 | -308 | -6.25 | -479 | -2.95 | 1,513 | 7.58 | 726 | 1.77 |
| 9 | -324 | -6.57 | 353 | 2.18 | -179 | -0.90 | -150 | -0.36 |
| 10 | -100 | -2.03 | 175 | 1.08 | 747 | 3.74 | 822 | 2.00 |
| **Avg.** | **20** | **0.41** | **-181** | **-1.11** | **548** | **2.75** | **388** | **0.94** |
| **St. Dev.** | **270** | **5.49** | **319** | **1.97** | **933** | **4.67** | **936** | **2.28** |
| **CV** | **1,339%** | **1,339%** | **-177%** | **-177%** | **170%** | **170%** | **242%** | **242%** |

APPENDIX B - ADJUSTED SYSTEM RELIABILITY RESULTS

**Table B.1 – Two Axle Straight Truck Adjusted Reliability Results**

| | WESTBOUND CURB LANE | | | EASTBOUND CURB LANE | | |
|---|---|---|---|---|---|---|
| **Axle Group** | **Steering** | **Drive** | **GVW** | **Steering** | **Drive** | **GVW** |
| Static Wt (kg) | 4,600 | 6,110 | 10,710 | 4,600 | 6,110 | 10,710 |
| Trial 1 | 4,923 | 5,996 | 10,919 | 5,043 | 6,863 | 11,906 |
| Trial 2 | 4,670 | 6,244 | 10,915 | 3,727 | 5,935 | 9,662 |
| Trial 3 | 4,711 | 6,289 | 11,000 | 5,247 | 7,040 | 12,287 |
| Trial 4 | 4,730 | 6,307 | 11,037 | 3,733 | 6,107 | 9,840 |
| Trial 5 | 4,874 | 6,263 | 11,137 | 4,684 | 6,322 | 11,006 |
| Trial 6 | 4,842 | 6,124 | 10,966 | 5,245 | 7,447 | 12,693 |
| Trial 7 | 4,713 | 6,444 | 11,157 | 5,268 | 7,360 | 12,628 |
| Trial 8 | 4,566 | 5,877 | 10,444 | 5,209 | 7,537 | 12,745 |
| Trial 9 | 4,834 | 6,161 | 10,994 | 5,089 | 6,930 | 12,020 |
| Trial 10 | 4,740 | 6,365 | 11,104 | 3,431 | 5,949 | 9,380 |
| Trial 11 | 4,695 | 5,881 | 10,576 | 5,239 | 7,788 | 13,027 |
| Trial 12 | 4,693 | 6,106 | 10,798 | 5,292 | 7,344 | 12,636 |
| Trial 13 | 4,687 | 6,375 | 11,061 | 5,931 | 8,003 | 13,934 |
| Trial 14 | 4,858 | 5,920 | 10,778 | 3,372 | 5,738 | 9,110 |
| Trial 15 | 4,593 | 6,179 | 10,772 | 5,156 | 7,610 | 12,766 |
| **Mean** | **4,742** | **6,169** | **10,911** | **4,778** | **6,932** | **11,709** |
| **St. Dev.** | **103.47** | **183.28** | **204.50** | **800.84** | **745.36** | **1,520.81** |
| **CV** | **2.18%** | **2.97%** | **1.87%** | **16.76%** | **10.75%** | **12.99%** |
| **Mean Diff.** | **-3.1%** | **-1.0%** | **-1.9%** | **-3.9%** | **-13.4%** | **-9.3%** |

**Table B.2 – Three Axle Straight Truck Adjusted Reliability Results**

| | WESTBOUND CURB LANE | | | EASTBOUND CURB LANE | | |
|---|---|---|---|---|---|---|
| **Axle Group** | **Steering** | **Drive** | **GVW** | **Steering** | **Drive** | **GVW** |
| Static Wt (kg) | 5,200 | 16,665 | 21,865 | 5,200 | 16,665 | 21,865 |
| Trial 1 | 5,620 | 18,490 | 23,980 | 6,428 | 14,945 | 21,373 |
| Trial 2 | 5,645 | 18,502 | 24,147 | 6,069 | 15,591 | 21,660 |
| Trial 3 | 5,798 | 18,042 | 23,839 | 6,572 | 15,718 | 22,290 |
| Trial 4 | 5,902 | 18,035 | 23,937 | 6,507 | 15,159 | 21,666 |
| Trial 5 | 5,667 | 18,091 | 23,758 | 5,731 | 13,944 | 19,675 |
| Trial 6 | 5,837 | 18,425 | 24,261 | 6,422 | 15,518 | 21,939 |
| Trial 7 | 5,731 | 18,160 | 23,890 | 6,224 | 16,068 | 22,292 |
| Trial 8 | 5,965 | 18,162 | 24,127 | 6,295 | 15,575 | 21,870 |
| Trial 9 | 5,647 | 18,317 | 23,964 | 6,226 | 16,415 | 22,641 |
| Trial 10 | 5,704 | 18,800 | 24,504 | 1,633 | 15,571 | 17,204 |
| Trial 11 | 5,408 | 17,145 | 22,553 | 6,312 | 15,936 | 22,247 |
| Trial 12 | 5,688 | 18,174 | 23,862 | 5,728 | 14,382 | 20,111 |
| Trial 13 | 5,743 | 17,624 | 23,366 | 5,920 | 14,576 | 20,496 |
| Trial 14 | 5,523 | 18,188 | 23,711 | 6,456 | 17,130 | 23,587 |
| Trial 15 | 5,637 | 18,531 | 24,168 | 6,699 | 17,938 | 24,636 |
| **Mean** | **5,701** | **18,179** | **23,871** | **5,948** | **15,631** | **21,579** |
| **St. Dev.** | **140.35** | **397.90** | **450.34** | **1,228.12** | **1,024.95** | **1,738.97** |
| **CV** | **2.46%** | **2.19%** | **1.89%** | **20.65%** | **6.56%** | **8.06%** |
| **Mean Diff.** | **-9.63%** | **-9.08%** | **-9.18%** | **-14.39%** | **6.20%** | **1.31%** |

**Table B.3 – Five Axle Semi-Trailer Truck Adjusted Reliability Results**

| | WESTBOUND CURB LANE | | | | EASTBOUND CURB LANE | | | |
|---|---|---|---|---|---|---|---|---|
| **Axle Group** | **Steering** | **Drive** | **Trailer Tandem** | **GVW** | **Steering** | **Drive** | **Trailer Tandem** | **GVW** |
| Static Wt (kg) | 5,025 | 13,760 | 14,705 | 33,490 | 5,025 | 13,760 | 14,705 | 33,490 |
| Trial 1 | 5,141 | 13,249 | 15,049 | 33,439 | 5,773 | 14,507 | 16,831 | 37,111 |
| Trial 2 | 5,262 | 13,298 | 15,536 | 34,096 | 5,744 | 14,769 | 15,732 | 36,245 |
| Trial 3 | 5,125 | 13,086 | 15,218 | 33,429 | 5,635 | 13,415 | 16,509 | 35,558 |
| Trial 4 | 4,956 | 13,055 | 15,033 | 33,044 | 5,604 | 14,094 | 17,022 | 36,720 |
| Trial 5 | 5,154 | 13,518 | 15,497 | 34,169 | 5,610 | 14,041 | 16,624 | 36,276 |
| Trial 6 | 5,296 | 13,288 | 15,732 | 34,316 | 3,964 | 10,673 | 9,157 | 23,794 |
| Trial 7 | 5,368 | 12,982 | 15,877 | 34,226 | 5,716 | 14,728 | 15,813 | 36,258 |
| Trial 8 | 5,117 | 13,102 | 15,116 | 33,335 | 5,803 | 14,286 | 17,135 | 37,225 |
| Trial 9 | 5,092 | 13,237 | 15,328 | 33,657 | 5,596 | 14,483 | 16,517 | 36,596 |
| Trial 10 | 5,137 | 12,778 | 15,349 | 33,264 | 5,888 | 14,625 | 16,395 | 36,908 |
| Trial 11 | 5,166 | 13,031 | 15,546 | 33,743 | 5,681 | 14,307 | 15,379 | 35,367 |
| Trial 12 | 5,209 | 13,267 | 15,183 | 33,659 | 5,393 | 14,684 | 16,055 | 36,132 |
| Trial 13 | 5,190 | 13,298 | 15,469 | 33,957 | 5,562 | 14,451 | 16,136 | 36,148 |
| Trial 14 | 5,052 | 12,900 | 14,827 | 32,779 | 5,671 | 14,627 | 17,754 | 38,052 |
| **Mean** | **5,162** | **13,149** | **15,340** | **33,651** | **5,546** | **14,121** | **15,933** | **35,599** |
| **St. Dev.** | **102.75** | **193.70** | **290.39** | **465.28** | **470.75** | **1,054.66** | **2,046.61** | **3,466.57** |
| **CV** | **1.99%** | **1.47%** | **1.89%** | **1.38%** | **8.49%** | **7.47%** | **12.85%** | **9.74%** |
| **Mean Diff.** | **-2.72%** | **4.44%** | **-4.32%** | **-0.48%** | **-10.36%** | **-2.62%** | **-8.35%** | **-6.30%** |

**Table B.4 – Six Axle Semi-Trailer Truck Adjusted Reliability Results**

| Axle Group | WESTBOUND CURB LANE Steering | Drive | Trailer Tridem | GVW | EASTBOUND CURB LANE Steering | Drive | Trailer Tridem | GVW |
|---|---|---|---|---|---|---|---|---|
| Static Wt (kg) | 4,755 | 17,860 | 13,195 | 35,810 | 4,755 | 17,860 | 13,195 | 35,810 |
| Trial 1 | 4,842 | 17,707 | 14,211 | 36,760 | 5,118 | 17,841 | 15,975 | 38,934 |
| Trial 2 | 4,444 | 17,775 | 13,706 | 35,924 | 6,734 | 21,450 | 15,606 | 43,790 |
| Trial 3 | 4,642 | 17,876 | 13,997 | 36,515 | 5,430 | 18,889 | 15,341 | 39,660 |
| Trial 4 | 4,725 | 17,872 | 14,048 | 36,646 | 5,249 | 18,621 | 15,807 | 39,678 |
| Trial 5 | 4,593 | 17,952 | 14,321 | 36,866 | 5,408 | 18,776 | 15,140 | 39,323 |
| Trial 6 | 4,732 | 18,476 | 14,684 | 37,891 | 5,393 | 18,826 | 15,102 | 39,321 |
| Trial 7 | 4,695 | 17,999 | 13,803 | 36,497 | 5,266 | 19,031 | 15,844 | 40,140 |
| Trial 8 | 4,817 | 17,885 | 13,602 | 36,303 | 5,241 | 18,336 | 15,525 | 39,102 |
| Trial 9 | 4,813 | 17,927 | 14,484 | 37,225 | 5,623 | 18,763 | 15,160 | 39,546 |
| Trial 10 | 4,658 | 18,390 | 14,160 | 37,209 | 5,381 | 18,461 | 15,104 | 38,946 |
| Trial 11 | 4,717 | 17,548 | 14,545 | 36,811 | 5,310 | 17,293 | 11,194 | 33,798 |
| Trial 12 | 4,603 | 17,738 | 14,686 | 37,027 | 5,337 | 18,555 | 15,953 | 39,844 |
| Trial 13 | 4,766 | 17,424 | 13,508 | 35,698 | 5,541 | 18,388 | 14,088 | 38,018 |
| Trial 14 | 4,624 | 17,781 | 13,736 | 36,140 | 5,249 | 19,031 | 16,095 | 40,376 |
| Trial 15 | 4,713 | 18,170 | 13,938 | 36,821 | 5,470 | 18,293 | 15,012 | 38,776 |
| **Mean** | **4,692** | **17,901** | **14,095** | **36,689** | **5,450** | **18,704** | **15,130** | **39,284** |
| **St. Dev.** | **103.35** | **280.73** | **388.22** | **552.38** | **377.70** | **887.99** | **1,204.49** | **1,984.57** |
| **CV** | **2.20%** | **1.57%** | **2.75%** | **1.51%** | **6.93%** | **4.75%** | **7.96%** | **5.05%** |
| **Mean Diff.** | **1.32%** | **-0.23%** | **-6.82%** | **-2.45%** | **-14.62%** | **-4.72%** | **-14.66%** | **-9.70%** |

**Table B.5 – Eight Axle Semi-Trailer Combination Unit Adjusted Reliability Results**

| Axle Group | WESTBOUND CURB LANE Steer | Drive | Trailer Tridem | Trailer Tandem | GVW | EASTBOUND CURB LANE Steer | Drive | Trailer Tridem | Trailer Tandem | GVW |
|---|---|---|---|---|---|---|---|---|---|---|
| Static Wt (kg) | 4,890 | 17,410 | 22,940 | 14,825 | 60,065 | 4,890 | 17,410 | 22,940 | 14,825 | 60,065 |
| Trial 1 | 4,899 | 17,143 | 23,970 | 15,561 | 61,572 | 5,541 | 18,861 | 25,505 | 16,947 | 66,854 |
| Trial 2 | 4,760 | 17,310 | 23,609 | 15,408 | 61,087 | 5,385 | 18,816 | 25,156 | 15,882 | 65,240 |
| Trial 3 | 4,683 | 16,957 | 21,658 | 15,055 | 58,353 | 5,511 | 18,263 | 25,171 | 15,665 | 64,609 |
| Trial 4 | 4,760 | 17,542 | 23,701 | 15,369 | 61,372 | 5,237 | 17,849 | 23,695 | 15,941 | 62,722 |
| Trial 5 | 4,760 | 17,008 | 22,812 | 15,210 | 59,790 | 5,282 | 17,685 | 23,605 | 16,128 | 62,699 |
| Trial 6 | 4,340 | 17,375 | 22,478 | 14,435 | 58,628 | 5,166 | 18,145 | 24,566 | 16,089 | 63,967 |
| Trial 7 | 4,630 | 17,740 | 23,318 | 15,263 | 60,950 | 5,493 | 18,263 | 23,248 | 15,613 | 62,616 |
| Trial 8 | 4,550 | 17,275 | 23,195 | 15,147 | 60,167 | 5,270 | 18,011 | 25,033 | 16,213 | 64,526 |
| Trial 9 | 4,689 | 17,648 | 22,957 | 15,108 | 60,402 | 5,422 | 18,382 | 25,448 | 16,864 | 66,116 |
| Trial 10 | 4,569 | 17,348 | 22,633 | 15,137 | 59,686 | 5,444 | 17,158 | 23,735 | 14,400 | 60,737 |
| Trial 11 | 4,564 | 17,518 | 22,630 | 15,574 | 60,286 | 5,367 | 18,141 | 24,968 | 16,223 | 64,699 |
| Trial 12 | 4,617 | 17,214 | 22,586 | 15,014 | 59,431 | 5,669 | 18,461 | 24,376 | 14,514 | 63,020 |
| Trial 13 | 4,695 | 17,118 | 22,787 | 14,980 | 59,580 | 5,217 | 18,218 | 24,512 | 15,716 | 63,663 |
| Trial 14 | 4,575 | 17,404 | 22,889 | 15,120 | 59,988 | 5,406 | 17,387 | 25,390 | 16,448 | 64,630 |
| Trial 15 | 4,605 | 16,682 | 23,036 | 14,421 | 58,744 | 5,262 | 16,608 | 22,097 | 15,027 | 58,993 |
| **Mean** | **4,646** | **17,285** | **22,951** | **15,120** | **60,002** | **5,378** | **18,016** | **24,434** | **15,844** | **63,673** |
| **St. Dev.** | **128.66** | **278.67** | **568.06** | **334.56** | **982.79** | **140.05** | **605.56** | **978.87** | **740.47** | **2,002.16** |
| **CV** | **2.77%** | **1.61%** | **2.48%** | **2.21%** | **1.64%** | **2.60%** | **3.36%** | **4.01%** | **4.67%** | **3.14%** |
| **Mean Diff.** | **5.0%** | **0.7%** | **0.0%** | **-2.0%** | **0.1%** | **-10.%** | **-3.5%** | **-6.5%** | **-6.9%** | **-6.0%** |

## APPENDIX C - DAILY VWIM SYSTEM ERROR FACTORS

**Table C.1 – Six Axle Semi-Trailer Combination Truck GVW WIM Error**

| | Lane 1 | Lane 2 | Lane 3 | Lane 4 |
|---|---|---|---|---|
| Remaining Error (Post-Calibration) | 0.0138 | -0.0094 | 0.0034 | 0.0193 |
| Final Error (Validation Assessment) | -0.0821 | - | - | -0.0051 |
| Difference | -0.0959 | - | - | -0.0244 |
| Estimated Linear Daily Shift (% of Final Error) | 8.34% | 8.34% | 34.17% | 34.17% |

**Table C.2 – GVW WIM Error All Configurations**

| | Lane 1 | Lane 2 | Lane 3 | Lane 4 |
|---|---|---|---|---|
| **TWO AXLE STRAIGHT TRUCK** | | | | |
| Final Error | -0.078 | - | - | 0.001 |
| Daily Shift (% of Final Error) | 8.34% | 8.34% | 34.17% | 34.17% |
| Daily Shift Factor | -0.0065079 | -0.00651 | 0.000342 | 0.000342 |
| **THREE AXLE STRAIGHT TRUCK** | | | | |
| Final Error | 0.0318 | - | - | -0.0715 |
| Daily Shift (% of Final Error) | 8.34% | 8.34% | 34.17% | 34.17% |
| Daily Shift Factor | 0.00265323 | 0.002653 | -0.02443 | -0.02443 |
| **FIVE AXLE TRACTOR SEMI-TRAILER** | | | | |
| Final Error | -0.0485 | - | - | 0.0142 |
| Daily Shift (% of Final Error) | 8.34% | 8.34% | 34.17% | 34.17% |
| Daily Shift Factor | -0.0040466 | -0.00405 | 0.004853 | 0.004853 |
| **SIX AXLE TRACTOR SEMI-TRAILER** | | | | |
| Final Error | -0.0821 | - | - | -0.0051 |
| Daily Shift (% of Final Error) | 8.34% | 0.00% | 0.00% | 34.17% |
| Daily Shift Factor | -0.00685 | -0.00685 | -0.00174 | -0.00174 |
| **EIGHT AXLE COMBINATION UNIT** | | | | |
| Final Error | -0.046 | - | - | 0.02 |
| Daily Shift (% of Final Error) | 8.34% | 8.34% | 34.17% | 34.17% |
| Daily Shift Factor | -0.003838 | -0.00384 | 0.006835 | 0.006835 |

**Table C.3 – Six Axle Semi-Trailer Combination Truck Axle Group WIM Error**

| Axle Group | Lane 1 | Lane 2 | Lane 3 | Lane 4 |
|---|---|---|---|---|
| **POST CALIBRATION ERROR** | | | | |
| Steering | -0.0787 | -0.0041 | -0.001 | -0.0315 |
| Drive | 0.0122 | 0.0111 | 0.0187 | -0.0016 |
| Trailer Tridem | 0.038 | -0.0275 | -0.0083 | 0.0488 |
| **VALIDATION ERROR (FINAL ERROR)** | | | | |
| Steering | -0.1306 | - | - | 0.0319 |
| Drive | -0.033 | - | - | 0.0167 |
| Trailer Tridem | -0.131 | - | - | -0.048 |
| **DIFFERENCE IN ERROR** | | | | |
| Steering | -0.0519 | - | - | 0.0634 |
| Drive | -0.0452 | - | - | 0.0183 |
| Trailer Tridem | -0.169 | - | - | -0.0968 |
| **ESTIMATED LINEAR DAILY ERROR (% OF FINAL ERROR)** | | | | |
| Steering | 2.84% | 2.84% | 14.20% | 14.20% |
| Drive | 9.78% | 9.78% | 7.83% | 7.83% |
| Trailer Tridem | 9.21% | 9.21% | 14.40% | 14040% |

**Table C.4 – Steer Axle Group WIM Error All Configurations**

| | Lane 1 | Lane 2 | Lane 3 | Lane 4 |
|---|---|---|---|---|
| **TWO AXLE STRAIGHT TRUCK** | | | | |
| Final Error (Validation) | -0.024 | -0.024 | -0.011 | -0.011 |
| Daily Shift (% of Final Error) | 2.84% | 2.84% | 14.20% | 14.20% |
| Daily Shift Factor | -0.00068 | -0.00068 | -0.00156 | -0.00156 |
| **THREE AXLE STRAIGHT TRUCK** | | | | |
| Final Error (Validation) | -0.1222 | -0.1222 | -0.0756 | -0.0756 |
| Daily Shift (% of Final Error) | 2.84% | 2.84% | 14.20% | 14.20% |
| Daily Shift Factor | -0.00347 | -0.00347 | -0.01073 | -0.01073 |
| **FIVE AXLE TRACTOR SEMI-TRAILER** | | | | |
| Final Error (Validation) | -0.0886 | -0.0886 | -0.0078 | -0.0078 |
| Daily Shift (% of Final Error) | 2.84% | 2.84% | 14.20% | 14.20% |
| Daily Shift Factor | -0.00251 | -0.00251 | -0.00111 | -0.00111 |
| **SIX AXLE TRACTOR SEMI-TRAILER** | | | | |
| Final Error (Validation) | -0.1306 | -0.1306 | 0.0319 | 0.0319 |
| Daily Shift (% of Final Error) | 2.84% | 2.84% | 14.20% | 14.20% |
| Daily Shift Factor | -0.00371 | -0.00371 | 0.004529 | 0.004529 |
| **EIGHT AXLE COMBINATION UNIT** | | | | |
| Final Error (Validation) | -0.085 | -0.085 | 0.068 | 0.068 |
| Daily Shift (% of Final Error) | 2.84% | 2.84% | 14.20% | 14.20% |
| Daily Shift Factor | -0.00241 | -0.00241 | 0.009653 | 0.009653 |

Table C.5 – Drive Axle Group WIM Error All Configurations

| | Lane 1 | Lane 2 | Lane 3 | Lane 4 |
|---|---|---|---|---|
| **TWO AXLE STRAIGHT TRUCK** | | | | |
| Final Error (Validation) | -0.119 | -0.119 | 0.01 | 0.01 |
| Daily Shift (% of Final Error) | 9.78% | 9.78% | 7.83% | 7.83% |
| Daily Shift Factor | -0.01164 | 0.007807 | -0.00549 | -0.00549 |
| **THREE AXLE STRAIGHT TRUCK** | | | | |
| Final Error (Validation) | 0.0798 | 0.0798 | -0.0702 | -0.0702 |
| Daily Shift (% of Final Error) | 9.78% | 9.78% | 7.83% | 7.83% |
| Daily Shift Factor | 0.007807 | 0.007807 | -0.00549 | -0.00549 |
| **FIVE AXLE TRACTOR SEMI-TRAILER** | | | | |
| Final Error (Validation) | -0.0123 | -0.0123 | 0.0625 | 0.0625 |
| Daily Shift (% of Final Error) | 9.78% | 9.78% | 7.83% | 7.83% |
| Daily Shift Factor | -0.0012 | -0.0012 | 0.004892 | 0.004892 |
| **SIX AXLE TRACTOR SEMI-TRAILER** | | | | |
| Final Error (Validation) | -0.03 | -0.03 | 0.0167 | 0.0167 |
| Daily Shift (% of Final Error) | 9.78% | 9.78% | 7.83% | 7.83% |
| Daily Shift Factor | -0.03 | -0.03 | 0.0167 | 0.0167 |
| **EIGHT AXLE COMBINATION UNIT** | | | | |
| Final Error (Validation) | -0.021 | -0.021 | 0.026 | 0.026 |
| Daily Shift (% of Final Error) | 9.78% | 9.78% | 7.83% | 7.83% |
| Daily Shift Factor | -0.00205 | -0.00205 | 0.002035 | 0.002035 |

Table C.6 – Trailer Tridem Axle Group WIM Error All Configurations

| | Lane 1 | Lane 2 | Lane 3 | Lane 4 |
|---|---|---|---|---|
| **SIX AXLE TRACTOR SEMI-TRAILER** | | | | |
| Final Error (Validation) | -0.131 | -0.131 | -0.048 | -0.048 |
| Daily Shift (% of Final Error) | 9.21% | 9.21% | 14.40% | 14.40% |
| Daily Shift Factor | -0.01207 | -0.01207 | -0.00691 | -0.00691 |
| **EIGHT AXLE COMBINATION UNIT** | | | | |
| Final Error (Validation) | -0.051 | -0.051 | 0.018 | 0.018 |
| Daily Shift (% of Final Error) | 9.21% | 9.21% | 14.40% | 14.40% |
| Daily Shift Factor | -0.0047 | -0.0047 | 0.002593 | 0.002593 |

Table C.7 – Trailer Tandem Axle Group WIM Error All Configurations

| | Lane 1 | Lane 2 | Lane 3 | Lane 4 |
|---|---|---|---|---|
| **FIVE AXLE TRACTOR SEMI-TRAILER** | | | | |
| Final Error (Validation) | -0.0687 | -0.0687 | -0.0234 | -0.0234 |
| Daily Shift (% of Final Error) | 9.21% | 9.21% | 14.40% | 14.40% |
| Daily Shift Factor | -0.00633 | -0.00633 | -0.00337 | -0.00337 |
| **EIGHT AXLE COMBINATION UNIT** | | | | |
| Final Error (Validation) | -0.054 | -0.054 | -0.001 | -0.001 |
| Daily Shift (% of Final Error) | 9.21% | 9.21% | 14.40% | 14.40% |
| Daily Shift Factor | -0.00498 | -0.00498 | -0.00014 | -0.00014 |

## APPENDIX D - VEHICLE COUNT AND GVW ANALYSIS

**Table D.1 – Two and Three Axle Straight Truck**

| | | TWO AXLE STRAIGHT TRUCK | | | | | THREE AXLE STRAIGHT TRUCK | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Lane** | **Cnt** | **Avg.** | **St. Dev.** | **Max** | **Min** | **Cnt** | **Avg.** | **St. Dev** | **Max** | **Min** |
| 12-May-06 | 1 | 277 | 10,010 | 2,510 | 17,985 | 6,081 | 245 | 16,067 | 4,861 | 27,313 | 7,006 |
| | 2 | 91 | 9,723 | 2,779 | 17,414 | 6,117 | 141 | 12,967 | 5,577 | 29,976 | 1,593 |
| | 3 | 52 | 8,705 | 2,135 | 14,277 | 6,022 | 44 | 18,545 | 6,583 | 29,273 | 2,831 |
| | 4 | 232 | 9,341 | 2,328 | 16,222 | 6,005 | 324 | 18,467 | 7,733 | 36,455 | 2,290 |
| | **All** | **652** | **9,571** | **2,460** | **17,985** | **6,005** | **754** | **14,784** | **5,676** | **36,455** | **1,593** |
| 13-May-06 | 1 | 70 | 10,189 | 2,817 | 21,545 | 6,323 | 61 | 15,131 | 5,246 | 25,892 | 2,601 |
| | 2 | 18 | 9,874 | 2,811 | 15,798 | 6,124 | 23 | 11,240 | 4,538 | 21,506 | 2,120 |
| | 3 | 13 | 7,293 | 1,244 | 10,409 | 6,070 | 11 | 17,637 | 8,362 | 31,156 | 5,928 |
| | 4 | 56 | 9,869 | 2,364 | 14,922 | 6,113 | 65 | 17,165 | 8,163 | 35,916 | 2,121 |
| | **All** | **157** | **9,776** | **2,642** | **21,545** | **6,070** | **160** | **13,973** | **5,919** | **35,916** | **2,120** |
| 14-May-06 | 1 | 26 | 9,638 | 3,183 | 17,432 | 6,015 | 35 | 14,100 | 4,222 | 23,243 | 6,926 |
| | 2 | 3 | 8,832 | 1,368 | 9,888 | 7,287 | 8 | 9,651 | 5,192 | 20,718 | 2,368 |
| | 3 | 3 | 10,131 | 1,527 | 11,865 | 8,987 | 4 | 13,148 | 5,898 | 21,992 | 10,018 |
| | 4 | 19 | 10,335 | 3,403 | 19,674 | 6,444 | 33 | 13,885 | 7,663 | 31,574 | 2,287 |
| | **All** | **51** | **9,941** | **3,117** | **19,809** | **6,046** | **80** | **12,360** | **5,432** | **25,844** | **1,872** |
| 15-May-06 | 1 | 245 | 10,410 | 2,696 | 19,109 | 6,005 | 191 | 16,731 | 5,284 | 27,157 | 1,321 |
| | 2 | 102 | 9,555 | 2,293 | 18,113 | 6,206 | 157 | 13,111 | 5,372 | 27,795 | 1,923 |
| | 3 | 46 | 8,932 | 2,051 | 14,703 | 6,111 | 66 | 17,204 | 6,841 | 36,124 | 2,134 |
| | 4 | 208 | 9,521 | 2,467 | 17,089 | 6,043 | 268 | 17,772 | 8,026 | 35,981 | 2,124 |
| | **All** | **601** | **9,844** | **2,550** | **19,109** | **6,005** | **682** | **14,907** | **6,062** | **30,172** | **1,318** |
| 16-May-06 | 1 | 248 | 10,067 | 2,652 | 22,728 | 5,978 | 201 | 17,300 | 5,046 | 26,402 | 5,957 |
| | 2 | 93 | 9,163 | 2,204 | 15,124 | 6,164 | 120 | 15,091 | 6,173 | 31,464 | 2,680 |
| | 3 | 42 | 9,134 | 1,899 | 13,325 | 6,350 | 71 | 12,738 | 6,186 | 32,216 | 1,697 |
| | 4 | 213 | 9,378 | 2,663 | 20,405 | 6,045 | 242 | 15,493 | 7,260 | 38,242 | 1,752 |
| | **All** | **596** | **9,614** | **2,569** | **22,728** | **5,978** | **634** | **14,556** | **6,100** | **38,242** | **1,697** |
| 17-May-06 | 1 | 241 | 9,925 | 2,422 | 16,695 | 5,974 | 189 | 18,396 | 5,398 | 32,006 | 6,259 |
| | 2 | 119 | 10,054 | 2,938 | 17,572 | 5,966 | 155 | 15,790 | 6,715 | 27,631 | 1,947 |
| | 3 | 40 | 9,528 | 2,618 | 15,194 | 6,079 | 79 | 14,515 | 7,346 | 32,131 | 1,878 |
| | 4 | 243 | 9,536 | 2,530 | 17,781 | 6,013 | 279 | 15,423 | 7,028 | 37,057 | 1,651 |
| | **All** | **643** | **9,778** | **2,580** | **17,781** | **5,966** | **702** | **15,133** | **6,433** | **37,057** | **1,651** |
| 18-May-06 | 1 | 70 | 10,824 | 2,317 | 16,100 | 6,219 | 56 | 16,932 | 5,260 | 25,948 | 9,450 |
| | 2 | 35 | 9,547 | 2,532 | 16,666 | 6,130 | 46 | 12,605 | 6,253 | 27,560 | 3,890 |
| | 3 | 12 | 9,371 | 1,975 | 13,607 | 6,535 | 21 | 9,821 | 6,648 | 22,144 | 1,278 |
| | 4 | 37 | 10,080 | 2,553 | 15,235 | 6,356 | 63 | 13,523 | 7,777 | 29,069 | 1,569 |
| | **All** | **154** | **10,242** | **2,448** | **16,666** | **6,130** | **186** | **13,904** | **6,923** | **29,069** | **1,278** |
| ALL DAYS | 1 | 1177 | 10,139 | | | | 978 | 16,821 | | | |
| | 2 | 461 | 9,645 | | | | 650 | 13,939 | | | |
| | 3 | 208 | 8,971 | | | | 296 | 15,052 | | | |
| | 4 | 1,008 | 9,508 | | | | 1,274 | 16,660 | | | |
| | **All** | 2,854 | 9,738 | | | | 3,198 | 14,689 | | | |

**Table D.2 – Four Axle (Tandem Steering) Straight Truck and Four Axle Semi-Tractor**

| | | 4 AXLE STRAIGHT | | | | | FOUR AXLE TRACTOR-SEMI | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Lane** | **Cnt.** | **Avg.** | **St. Dev** | **Max** | **Min** | **Cnt.** | **Avg.** | **St. Dev** | **Max** | **Min** |
| 12-May-06 | 1 | 15 | 27,549 | 9,435 | 43,943 | 15,016 | 42 | 10,984 | 5,113 | 28,230 | 4,837 |
| | 2 | 4 | 17,654 | 9,519 | 31,108 | 9,052 | 25 | 10,326 | 4,243 | 22,029 | 4,465 |
| | 3 | 1 | 6,381 | - | 6,381 | 6,381 | 13 | 10,031 | 7,823 | 32,369 | 4,772 |
| | 4 | 60 | 10,045 | 11,212 | 43,560 | 2,450 | 69 | 10,366 | 6,053 | 31,640 | 3,620 |
| | **All** | **80** | **13,492** | **12,391** | **43,943** | **2,450** | **149** | **10,504** | **5,662** | **32,369** | **3,620** |
| 13-May-06 | 1 | 1 | 21,150 | - | 21,150 | 21,150 | 19 | 8,176 | 3,686 | 18,548 | 4,277 |
| | 2 | 2 | 15,716 | 572 | 16,121 | 15,312 | 14 | 9,697 | 5,427 | 26,367 | 4,589 |
| | 3 | - | - | - | - | - | 6 | 11,002 | 2,888 | 15,916 | 7,107 |
| | 4 | 16 | 9,847 | 10,795 | 37,256 | 2,501 | 38 | 8,493 | 3,041 | 18,340 | 4,704 |
| | **All** | **19** | **11,010** | **10,297** | **37,256** | **2,501** | **77** | **8,829** | **3,739** | **26,367** | **4,277** |
| 14-May-06 | 1 | 1 | 16,064 | - | - | - | 7 | 6,632 | 1,218 | 9,062 | 5,560 |
| | 2 | - | - | - | - | - | 3 | 6,872 | 3,746 | 11,140 | 4,129 |
| | 3 | - | - | - | - | - | 4 | 7,914 | 1,202 | 8,843 | 6,187 |
| | 4 | - | - | - | - | - | 21 | 8,152 | 2,076 | 12,445 | 4,454 |
| | **All** | **1** | **16,064** | **-** | **-** | **-** | **35** | **7,711** | **2,043** | **12,445** | **4,129** |
| 15-May-06 | 1 | 18 | 26,107 | 8,186 | 44,119 | 16,558 | 39 | 12,893 | 6,039 | 26,178 | 4,013 |
| | 2 | 5 | 24,423 | 10,167 | 35,079 | 13,497 | 23 | 8,970 | 3,765 | 18,905 | 3,769 |
| | 3 | 1 | 23,640 | - | 23,640 | 23,640 | 14 | 9,357 | 3,331 | 15,267 | 5,353 |
| | 4 | 79 | 9,460 | 10,115 | 45,870 | 2,175 | 70 | 10,965 | 5,469 | 31,535 | 3,975 |
| | **All** | **103** | **13,233** | **11,871** | **45,870** | **2,175** | **146** | **11,011** | **5,368** | **31,535** | **3,769** |
| 16-May-06 | 1 | 12 | 26,209 | 8,208 | 35,367 | 13,766 | 48 | 11,247 | 5,019 | 23,329 | 4,214 |
| | 2 | 3 | 20,642 | 10,762 | 33,068 | 14,342 | 21 | 10,178 | 6,329 | 34,992 | 5,225 |
| | 3 | 24 | 4,122 | 3,295 | 14,777 | 2,133 | 15 | 9,429 | 2,235 | 13,424 | 6,318 |
| | 4 | 181 | 4,829 | 6,018 | 47,616 | 2,027 | 66 | 10,480 | 4,929 | 27,943 | 4,471 |
| | **All** | **220** | **6,134** | **7,884** | **47,616** | **2,027** | **150** | **10,578** | **4,970** | **34,992** | **4,214** |
| 17-May-06 | 1 | 15 | 23,542 | 8,346 | 32,329 | 8,307 | 37 | 11,173 | 5,138 | 21,485 | 3,647 |
| | 2 | 3 | 29,943 | 3,521 | 33,991 | 27,588 | 20 | 10,024 | 4,790 | 17,726 | 4,287 |
| | 3 | - | - | - | - | - | 15 | 8,230 | 4,799 | 23,978 | 5,193 |
| | 4 | 53 | 8,395 | 8,025 | 34,013 | 2,182 | 53 | 10,666 | 6,747 | 31,592 | 3,662 |
| | **All** | **71** | **12,506** | **10,679** | **34,013** | **2,182** | **125** | **10,421** | **5,803** | **31,592** | **3,647** |
| 18-May-06 | 1 | 5 | 26,864 | 9,104 | 33,998 | 11,090 | 13 | 11,794 | 5,374 | 22,375 | 4,238 |
| | 2 | 3 | 14,167 | 2,786 | 17,266 | 11,869 | 7 | 9,970 | 3,387 | 16,021 | 5,868 |
| | 3 | 8 | 8,213 | 7,555 | 22,066 | 1,637 | 7 | 9,852 | 5,693 | 21,671 | 6,183 |
| | 4 | 50 | 5,875 | 8,250 | 33,789 | 2,212 | 18 | 10,593 | 7,602 | 30,742 | 3,629 |
| | **All** | **66** | **8,125** | **9,767** | **33,998** | **1,637** | **45** | **10,728** | **6,062** | **30,742** | **3,629** |
| ALL DAYS | 1 | 67 | 25,707 | | | | 205 | 11,085 | | | |
| | 2 | 20 | 20,921 | | | | 113 | 9,777 | | | |
| | 3 | 34 | 11,918 | | | | 74 | 9,364 | | | |
| | 4 | 439 | 7,108 | | | | 335 | 10,222 | | | |
| | **All** | 560 | 9,717 | | | | 727 | 10,309 | | | |

**Table D.3 – Five and Six Axle Tractor-Semi**

| | | FIVE AXLE TRACTOR-SEMI | | | | | SIX AXLE TRACTOR-SEMI | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Lane** | **Cnt** | **Avg.** | **St. Dev.** | **Max** | **Min** | **Cnt** | **Avg.** | **St. Dev** | **Max** | **Min** |
| | 1 | 306 | 27,034 | 8,342 | 44,859 | 9,043 | 128 | 31,423 | 11,422 | 53,574 | 15,283 |
| | 2 | 124 | 19,232 | 8,881 | 42,077 | 3,782 | 69 | 22,409 | 11,814 | 50,484 | 7,397 |
| 12-May-06 | 3 | 38 | 24,191 | 8,029 | 39,403 | 12,940 | 24 | 24,600 | 11,054 | 46,788 | 12,298 |
| | 4 | 380 | 25,982 | 8,547 | 45,418 | 6,850 | 184 | 30,839 | 11,612 | 50,792 | 8,340 |
| | **All** | **848** | **25,897** | **9,133** | **45,418** | **3,782** | **405** | **28,968** | **11,864** | **53,574** | **7,397** |
| | 1 | 258 | 25,347 | 7,984 | 43,539 | 6,576 | 77 | 32,842 | 10,725 | 52,297 | 16,840 |
| | 2 | 60 | 21,735 | 9,301 | 40,056 | 10,226 | 29 | 21,006 | 10,487 | 45,280 | 10,604 |
| 13-May-06 | 3 | 30 | 21,863 | 9,314 | 43,657 | 7,527 | 10 | 21,937 | 8,427 | 38,279 | 11,355 |
| | 4 | 268 | 29,802 | 8,262 | 42,942 | 13,382 | 80 | 30,925 | 10,800 | 49,635 | 12,568 |
| | **All** | **616** | **27,409** | **9,162** | **43,657** | **6,576** | **196** | **29,554** | **11,319** | **52,297** | **10,604** |
| | 1 | 79 | 27,297 | 6,998 | 42,097 | 14,349 | 38 | 33,011 | 9,836 | 47,678 | 18,089 |
| | 2 | 16 | 23,815 | 6,793 | 34,804 | 13,814 | 5 | 24,157 | 10,176 | 36,665 | 14,099 |
| 14-May-06 | 3 | 23 | 25,777 | 5,968 | 33,425 | 15,197 | 7 | 32,293 | 8,369 | 42,010 | 19,471 |
| | 4 | 249 | 28,732 | 6,099 | 40,637 | 7,235 | 71 | 37,311 | 8,708 | 49,324 | 17,055 |
| | **All** | **367** | **28,912** | **6,676** | **42,294** | **7,530** | **121** | **34,928** | **9,379** | **48,640** | **14,534** |
| | 1 | 260 | 25,527 | 7,607 | 45,668 | 11,185 | 125 | 31,472 | 10,570 | 52,820 | 13,894 |
| | 2 | 137 | 18,216 | 7,903 | 41,222 | 9,128 | 84 | 22,571 | 12,443 | 47,813 | 9,113 |
| 15-May-06 | 3 | 57 | 28,716 | 7,771 | 39,684 | 13,645 | 32 | 27,999 | 10,656 | 46,327 | 14,244 |
| | 4 | 436 | 27,123 | 8,623 | 46,466 | 12,239 | 210 | 31,275 | 11,586 | 51,862 | 11,948 |
| | **All** | **890** | **26,008** | **9,054** | **48,118** | **9,202** | **451** | **29,587** | **11,859** | **53,548** | **9,461** |
| | 1 | 263 | 27,038 | 8,000 | 47,033 | 10,948 | 143 | 30,804 | 10,251 | 52,384 | 8,877 |
| | 2 | 101 | 19,561 | 8,317 | 39,418 | 6,035 | 84 | 23,117 | 11,484 | 51,213 | 6,964 |
| 16-May-06 | 3 | 59 | 24,093 | 9,490 | 40,919 | 4,004 | 38 | 28,120 | 10,575 | 47,412 | 13,220 |
| | 4 | 282 | 24,932 | 8,371 | 41,713 | 5,905 | 185 | 32,600 | 11,307 | 56,261 | 10,882 |
| | **All** | **705** | **25,400** | **8,834** | **47,033** | **4,004** | **450** | **30,155** | **11,457** | **56,261** | **6,964** |
| | 1 | 276 | 27,264 | 7,892 | 43,771 | 11,021 | 128 | 32,587 | 10,016 | 52,230 | 14,974 |
| | 2 | 116 | 19,285 | 8,431 | 43,101 | 6,737 | 87 | 23,395 | 13,237 | 46,810 | 6,217 |
| 17-May-06 | 3 | 51 | 23,192 | 8,177 | 39,279 | 10,215 | 27 | 28,349 | 10,895 | 45,537 | 13,895 |
| | 4 | 348 | 26,366 | 8,620 | 46,270 | 8,601 | 214 | 31,318 | 11,580 | 50,515 | 11,684 |
| | **All** | **791** | **25,969** | **8,925** | **46,270** | **6,737** | **456** | **30,364** | **12,014** | **52,230** | **6,217** |
| | 1 | 102 | 27,512 | 7,212 | 40,136 | 7,888 | 63 | 32,936 | 10,690 | 50,900 | 14,050 |
| | 2 | 57 | 17,349 | 10,396 | 43,410 | 5,658 | 40 | 21,409 | 10,423 | 46,050 | 8,489 |
| 18-May-06 | 3 | 54 | 27,698 | 7,206 | 39,723 | 13,644 | 31 | 30,859 | 11,560 | 47,481 | 10,616 |
| | 4 | 80 | 28,131 | 9,004 | 45,607 | 9,903 | 48 | 28,635 | 11,180 | 51,744 | 12,482 |
| | **All** | **293** | **25,738** | **9,338** | **45,607** | **5,658** | **182** | **28,914** | **11,658** | **51,744** | **8,489** |
| | 1 | 1,544 | 26,585 | | | | 702 | 31,895 | | | |
| | 2 | 611 | 19,259 | | | | 398 | 22,628 | | | |
| ALL DAYS | 3 | 312 | 25,336 | | | | 169 | 27,943 | | | |
| | 4 | 2,043 | 27,066 | | | | 992 | 31,727 | | | |
| | **All** | 4,510 | 26,295 | | | | 2,261 | 29,975 | | | |

**Table D.4 – Eight Axle Tractor-Semi Combination Unit**

| | | EIGHT AXLE TRACTOR-SEMI COMBINATION UNIT | | | | |
|---|---|---|---|---|---|---|
| **Date** | **Lane** | **Cnt** | **Avg.** | **St. Dev.** | **Max** | **Min** |
| 12-May-06 | 1 | 144 | 45,336 | 18,628 | 73,140 | 19,379 |
| | 2 | 66 | 35,675 | 21,003 | 64,922 | 10,078 |
| | 3 | 20 | 30,712 | 17,115 | 56,578 | 9,238 |
| | 4 | 170 | 44,978 | 17,449 | 65,985 | 10,196 |
| | **All** | **400** | **44,223** | **19,589** | **73,140** | **9,238** |
| 13-May-06 | 1 | 105 | 43,226 | 19,225 | 75,226 | 15,585 |
| | 2 | 57 | 28,405 | 18,702 | 66,468 | 11,139 |
| | 3 | 15 | 41,627 | 18,033 | 60,211 | 11,686 |
| | 4 | 131 | 46,545 | 17,010 | 68,427 | 16,668 |
| | **All** | **308** | **43,167** | **20,003** | **75,226** | **11,139** |
| 14-May-06 | 1 | 76 | 44,303 | 19,217 | 75,572 | 20,804 |
| | 2 | 28 | 35,462 | 21,022 | 65,817 | 8,433 |
| | 3 | 12 | 39,766 | 19,464 | 58,785 | 14,965 |
| | 4 | 100 | 50,667 | 15,280 | 68,924 | 18,413 |
| | **All** | **216** | **47,310** | **19,113** | **76,152** | **8,498** |
| 15-May-06 | 1 | 165 | 43,445 | 18,363 | 70,902 | 13,337 |
| | 2 | 53 | 31,101 | 19,041 | 68,121 | 13,591 |
| | 3 | 31 | 32,767 | 16,932 | 59,603 | 12,001 |
| | 4 | 173 | 42,517 | 18,371 | 68,131 | 14,546 |
| | **All** | **422** | **41,831** | **19,359** | **71,724** | **12,521** |
| 16-May-06 | 1 | 161 | 48,581 | 17,780 | 74,847 | 18,585 |
| | 2 | 72 | 35,227 | 21,882 | 67,025 | 6,213 |
| | 3 | 31 | 38,437 | 18,444 | 62,106 | 12,518 |
| | 4 | 193 | 44,628 | 18,339 | 67,766 | 15,152 |
| | **All** | **457** | **45,242** | **19,742** | **74,847** | **6,213** |
| 17-May-06 | 1 | 168 | 43,696 | 18,564 | 74,532 | 17,165 |
| | 2 | 80 | 34,012 | 21,084 | 64,776 | 9,804 |
| | 3 | 21 | 45,205 | 18,030 | 62,463 | 13,765 |
| | 4 | 211 | 45,095 | 18,527 | 69,892 | 5,353 |
| | **All** | **480** | **43,796** | **19,800** | **69,892** | **5,353** |
| 18-May-06 | 1 | 57 | 46,438 | 17,722 | 73,534 | 11,065 |
| | 2 | 21 | 30,982 | 20,558 | 61,777 | 14,001 |
| | 3 | 26 | 52,330 | 14,762 | 64,665 | 17,297 |
| | 4 | 28 | 43,248 | 14,733 | 64,685 | 21,021 |
| | **All** | **132** | **44,463** | **18,126** | **73,534** | **11,065** |
| ALL DAYS | 1 | 876 | 44,991 | | | |
| | 2 | 377 | 33,217 | | | |
| | 3 | 156 | 39,956 | | | |
| | 4 | 1,006 | 45,234 | | | |
| | **All** | 2,415 | 44,068 | | | |

## APPENDIX E - ESAL REGRESSION ANALYSIS

### Table E.1 – Single Axle Load ESALF Best-Fit Equation Analysis

$P_t$ = 2.5  SN = 2
**Power Function**
y = 4E-16x3.9655
$R^2$ = 0.9951
**Polynomial Function**
y = 7E-25x6 – 3E-20x5 + 1E-15x4 – 1E-11x3 + 8E-8x2 – 0.0002x + 0.1383
$R^2$ = 1

| Single Axle Load (kips) | ESALF | Axle Load (kg) | Polynomial | | Power Function | | Best Fit Test |
|---|---|---|---|---|---|---|---|
| | | | Test from Equation | Diff | Test from Equation | Diff | |
| 2 | 0.0004 | 907 | 0.016 | -0.015 | 0.0002 | 0.0002 | Power Function |
| 4 | 0.004 | 1,814 | -0.011 | 0.015 | 0.0033 | 0.0007 | Power Function |
| 6 | 0.017 | 2,722 | 0.036 | -0.019 | 0.0167 | 0.0003 | Power Function |
| 8 | 0.047 | 3,629 | 0.144 | -0.097 | 0.0523 | -0.0053 | Power Function |
| 10 | 0.102 | 4,536 | 0.316 | -0.214 | 0.1266 | -0.0246 | Power Function |
| 12 | 0.198 | 5,443 | 0.560 | -0.362 | 0.2610 | -0.0630 | Power Function |
| 14 | 0.358 | 6,350 | 0.896 | -0.538 | 0.4809 | -0.1229 | Power Function |
| 16 | 0.613 | 7,258 | 1.350 | -0.737 | 0.8166 | -0.2036 | Power Function |
| 18 | 1 | 8,165 | 1.96 | -0.958 | 1.3028 | -0.3028 | Power Function |
| 20 | 1.57 | 9,072 | 2.76 | -1.192 | 1.9785 | -0.4085 | Power Function |
| 22 | 2.38 | 9,979 | 3.81 | -1.431 | 2.8872 | -0.5072 | Power Function |
| 24 | 3.49 | 10,886 | 5.16 | -1.674 | 4.0768 | -0.5868 | Power Function |
| 26 | 4.99 | 11,794 | 6.89 | -1.898 | 5.5998 | -0.6098 | Power Function |
| 28 | 6.98 | 12,701 | 9.06 | -2.080 | 7.5128 | -0.5328 | Power Function |
| 30 | 9.5 | 13,608 | 11.77 | -2.269 | 9.8769 | -0.3769 | Power Function |
| 32 | 12.8 | 14,515 | 15.116 | -2.316 | 12.7576 | 0.0424 | Power Function |
| 34 | 16.9 | 15,422 | 19.217 | -2.317 | 16.2247 | 0.6753 | Power Function |
| 36 | 22 | 16,330 | 24.205 | -2.205 | 20.3523 | 1.6477 | Power Function |
| 38 | 28.3 | 17,237 | 30.233 | -1.933 | 25.2191 | 3.0809 | Polynomial |
| 40 | 35.9 | 18,144 | 37.474 | -1.574 | 30.9076 | 4.9924 | Polynomial |
| 42 | 45 | 19,051 | 46.128 | -1.128 | 37.5052 | 7.4948 | Polynomial |
| 44 | 55.9 | 19,958 | 56.423 | -0.523 | 45.1033 | 10.7967 | Polynomial |
| 46 | 68.8 | 20,866 | 68.617 | 0.183 | 53.7976 | 15.0024 | Polynomial |
| 48 | 83.9 | 21,773 | 83.006 | 0.894 | 63.6882 | 20.2118 | Polynomial |
| 50 | 102 | 22,680 | 99.924 | 2.076 | 74.8794 | 27.1206 | Polynomial |

**Table E.2 - Tandem Axle Load ESALF Best-Fit Equation Analysis**

$p_t = 2.5$ SN = 2

**Power Function**

y = 2E-16x3.8097 $R^2 = 0.9926$

**Polynomial Function**

y = -2E-27x6 + 7E-22x5 + 5E-18x4 + 3E-14x3 + 5E-10x2 - 2E-08x - 0.0021 $R^2 = 1$

| Tandem Axle Load (kips) | ESALF | Axle Load (kg) | Polynomial Eqt'n Test | Polynomial Diff | Power Function Eqt'n Test | Power Function Diff | Best Fit Test |
|---|---|---|---|---|---|---|---|
| 2 | 0.0001 | 907 | -0.002 | 0.002 | 3.707E-05 | 6.293E-05 | Power Function |
| 4 | 0.0005 | 1,814 | 0.000 | 0.001 | 5.198E-04 | -1.979E-05 | Power Function |
| 6 | 0.002 | 2,722 | 0.003 | -0.001 | 2.436E-03 | -4.360E-04 | Power Function |
| 8 | 0.006 | 3,629 | 0.007 | -0.001 | 7.289E-03 | -1.289E-03 | Polynomial |
| 10 | 0.013 | 4,536 | 0.014 | -0.001 | 1.706E-02 | -4.055E-03 | Polynomial |
| 12 | 0.024 | 5,443 | 0.025 | -0.001 | 3.416E-02 | -1.016E-02 | Polynomial |
| 14 | 0.041 | 6,350 | 0.041 | 0.000 | 6.146E-02 | -2.046E-02 | Polynomial |
| 16 | 0.065 | 7,258 | 0.063 | 0.002 | 1.022E-01 | -3.721E-02 | Polynomial |
| 18 | 0.097 | 8,165 | 0.094 | 0.003 | 1.601E-01 | -6.309E-02 | Polynomial |
| 20 | 0.141 | 9,072 | 0.137 | 0.004 | 2.392E-01 | -9.816E-02 | Polynomial |
| 22 | 0.198 | 9,979 | 0.194 | 0.004 | 3.439E-01 | -1.459E-01 | Polynomial |
| 24 | 0.273 | 10,886 | 0.270 | 0.003 | 4.790E-01 | -2.060E-01 | Polynomial |
| 26 | 0.37 | 11,794 | 0.37 | 0.003 | 6.498E-01 | -2.798E-01 | Polynomial |
| 28 | 0.493 | 12,701 | 0.49 | 0.000 | 8.618E-01 | -3.688E-01 | Polynomial |
| 30 | 0.648 | 13,608 | 0.65 | -0.003 | 1.121E+00 | -4.728E-01 | Polynomial |
| 32 | 0.843 | 14,515 | 0.85 | -0.006 | 1.433E+00 | -5.903E-01 | Polynomial |
| 34 | 1.08 | 15,422 | 1.09 | -0.013 | 1.806E+00 | -7.256E-01 | Polynomial |
| 36 | 1.38 | 16,330 | 1.39 | -0.012 | 2.245E+00 | -8.649E-01 | Polynomial |
| 38 | 1.73 | 17,237 | 1.75 | -0.024 | 2.758E+00 | -1.028E+00 | Polynomial |
| 40 | 2.16 | 18,144 | 2.19 | -0.028 | 3.354E+00 | -1.194E+00 | Polynomial |
| 42 | 2.67 | 19,051 | 2.71 | -0.036 | 4.039E+00 | -1.369E+00 | Polynomial |
| 44 | 3.27 | 19,958 | 3.32 | -0.049 | 4.822E+00 | -1.552E+00 | Polynomial |
| 46 | 3.98 | 20,866 | 4.04 | -0.059 | 5.712E+00 | -1.732E+00 | Polynomial |
| 48 | 4.8 | 21,773 | 4.88 | -0.080 | 6.717E+00 | -1.917E+00 | Polynomial |
| 50 | 5.76 | 22,680 | 5.86 | -0.096 | 7.847E+00 | -2.087E+00 | Polynomial |
| 52 | 6.87 | 23,587 | 6.98 | -0.113 | 9.112E+00 | -2.242E+00 | Polynomial |
| 54 | 8.14 | 24,494 | 8.28 | -0.138 | 1.052E+01 | -2.381E+00 | Polynomial |
| 56 | 9.6 | 25,402 | 9.76 | -0.159 | 1.208E+01 | -2.485E+00 | Polynomial |
| 58 | 11.3 | 26,309 | 11.44 | -0.145 | 1.381E+01 | -2.513E+00 | Polynomial |
| 60 | 13.1 | 27,216 | 13.4 | -0.255 | 1.572E+01 | -2.617E+00 | Polynomial |
| 62 | 15.3 | 28,123 | 15.5 | -0.213 | 1.781E+01 | -2.509E+00 | Polynomial |
| 64 | 17.6 | 29,030 | 17.9 | -0.340 | 2.010E+01 | -2.498E+00 | Polynomial |
| 66 | 20.3 | 29,938 | 20.7 | -0.361 | 2.260E+01 | -2.298E+00 | Polynomial |
| 68 | 23.3 | 30,845 | 23.7 | -0.401 | 2.532E+01 | -2.020E+00 | Polynomial |
| 70 | 26.6 | 31,752 | 27.1 | -0.486 | 2.828E+01 | -1.677E+00 | Polynomial |
| 72 | 30.3 | 32,659 | 30.8 | -0.546 | 3.148E+01 | -1.180E+00 | Polynomial |
| 74 | 34.4 | 33,566 | 35.0 | -0.610 | 3.494E+01 | -5.437E-01 | Power Function |
| 76 | 38.9 | 34,474 | 39.6 | -0.708 | 3.868E+01 | 2.194E-01 | Power Function |
| 78 | 43.9 | 35,381 | 44.7 | -0.773 | 4.270E+01 | 1.196E+00 | Polynomial |
| 80 | 49.4 | 36,288 | 50.2 | -0.839 | 4.703E+01 | 2.372E+00 | Polynomial |
| 82 | 55.4 | 37,195 | 56.3 | -0.942 | 5.167E+01 | 3.733E+00 | Polynomial |
| 84 | 61.9 | 38,102 | 63.0 | -1.117 | 5.663E+01 | 5.265E+00 | Polynomial |
| 86 | 69.1 | 39,010 | 70.3 | -1.204 | 6.195E+01 | 7.154E+00 | Polynomial |
| 88 | 76.9 | 39,917 | 78.2 | -1.343 | 6.762E+01 | 9.283E+00 | Polynomial |
| 90 | 85.4 | 40,824 | 86.9 | -1.475 | 7.366E+01 | 1.174E+01 | Polynomial |

**Table E.3 - Tridem Axle Load ESALF Best-Fit Equation Analysis**

$p_t = 2.5$ SN = 2

**Polynomial Function**

y = 3E-27x6 + 5E-22x5 - 1E-17x4 + 3E-13x3 - 2E-09x2 + 8E-06x - 0.0089)/2

$R^2 = 1$

| Tridem Axle Load (kips) | ESALF | Axle Load (kg) | Polynomial Equation Test | Polynomial Diff |
|---|---|---|---|---|
| 2 | 0 | 907 | -0.002 | 0.002 |
| 4 | 0.0002 | 1,814 | 0.000 | 0.000 |
| 6 | 0.0007 | 2,722 | 0.002 | -0.001 |
| 8 | 0.002 | 3,629 | 0.003 | -0.001 |
| 10 | 0.004 | 4,536 | 0.005 | -0.001 |
| 12 | 0.007 | 5,443 | 0.009 | -0.002 |
| 14 | 0.012 | 6,350 | 0.013 | -0.001 |
| 16 | 0.019 | 7,258 | 0.020 | -0.001 |
| 18 | 0.029 | 8,165 | 0.030 | -0.001 |
| 20 | 0.042 | 9,072 | 0.042 | 0.000 |
| 22 | 0.058 | 9,979 | 0.059 | -0.001 |
| 24 | 0.078 | 10,886 | 0.080 | -0.002 |
| 26 | 0.103 | 11,794 | 0.106 | -0.003 |
| 28 | 0.133 | 12,701 | 0.139 | -0.006 |
| 30 | 0.169 | 13,608 | 0.178 | -0.009 |
| 32 | 0.213 | 14,515 | 0.227 | -0.014 |
| 34 | 0.266 | 15,422 | 0.285 | -0.019 |
| 36 | 0.329 | 16,330 | 0.354 | -0.025 |
| 38 | 0.403 | 17,237 | 0.435 | -0.032 |
| 40 | 0.491 | 18,144 | 0.531 | -0.040 |
| 42 | 0.594 | 19,051 | 0.643 | -0.049 |
| 44 | 0.714 | 19,958 | 0.773 | -0.059 |
| 46 | 0.854 | 20,866 | 0.924 | -0.070 |
| 48 | 1.015 | 21,773 | 1.097 | -0.082 |
| 50 | 1.2 | 22,680 | 1.29 | -0.095 |
| 52 | 1.41 | 23,587 | 1.52 | -0.111 |
| 54 | 1.66 | 24,494 | 1.78 | -0.118 |
| 56 | 1.93 | 25,402 | 2.07 | -0.140 |
| 58 | 2.25 | 26,309 | 2.40 | -0.148 |
| 60 | 2.6 | 27,216 | 2.77 | -0.168 |
| 62 | 3 | 28,123 | 3.18 | -0.182 |
| 64 | 3.44 | 29,030 | 3.64 | -0.204 |
| 66 | 3.94 | 29,938 | 4.16 | -0.220 |
| 68 | 4.49 | 30,845 | 4.73 | -0.242 |
| 70 | 5.11 | 31,752 | 5.37 | -0.255 |
| 72 | 5.79 | 32,659 | 6.07 | -0.275 |
| 74 | 6.54 | 33,566 | 6.84 | -0.296 |
| 76 | 7.37 | 34,474 | 7.68 | -0.313 |
| 78 | 8.28 | 35,381 | 8.61 | -0.332 |
| 80 | 9.28 | 36,288 | 9.63 | -0.347 |
| 82 | 10.4 | 37,195 | 10.74 | -0.336 |
| 84 | 11.6 | 38,102 | 11.94 | -0.342 |
| 86 | 12.9 | 39,010 | 13.25 | -0.354 |
| 88 | 14.3 | 39,917 | 14.68 | -0.375 |
| 90 | 15.8 | 40,824 | 16.21 | -0.414 |

# APPENDIX F - OVERWEIGHT ESAL ANALYSIS

**Table F.1 –Westbound Curb Lane Overweight ESALs by Vehicle Class**

| | Steering | Drive | Trailer Tridem | Trailer Tandem |
|---|---|---|---|---|
| **TWO AXLE STRAIGHT TRUCK** | | | | |
| Legal ESAL Limit (SDHT) | 1.226 | 1.57 | - | - |
| No. of Records Over Limit | 4 | 126 | - | - |
| % Records Over Limits | 0% | 13% | - | - |
| Avg. ESALs per Over Record | 2.650 | 3.076 | - | - |
| Sum of ESALs from Over Records | 11 | 388 | - | - |
| Total ESALs Over Limit | 6 | 190 | - | - |
| **THREE AXLE STRAIGHT TRUCK** | | | | |
| Legal ESAL Limit (SDHT) | 1.226 | 1.73 | - | - |
| No. of Records Over Limit | 156 | 128 | - | - |
| % Records Over Limits | 12% | 10% | - | - |
| Avg. ESALs per Over Record | 2.463 | 2.701 | - | - |
| Sum of ESALs from Over Records | 384 | 346 | - | - |
| Total ESALs Over Limit | 193 | 124 | - | - |
| **FOUR AXLE STRAIGHT TRUCK W/TANDEM STEERING** | | | | |
| Legal ESAL Limit (SDHT) | 1.296 | 2.160 | - | - |
| No. of Records Over Limit | 18 | 12 | - | - |
| % Records Over Limits | 4% | 3% | - | - |
| Avg. ESALs per Over Record | 2.953 | 4.811 | - | - |
| Sum of ESALs from Over Records | 53 | 58 | - | - |
| Total ESALs Over Limit | 30 | 32 | - | - |
| **FOUR AXLE TRACTOR-SEMI** | | | | |
| Legal ESAL Limit (SDHT) | 0.396 | 1.570 | - | 1.730 |
| No. of Records Over Limit | 18 | 16 | - | 3 |
| % Records Over Limits | 4% | 4% | - | 1% |
| Avg. ESALs per Over Record | 0.991 | 2.776 | - | 2.635 |
| Sum of ESALs from Over Records | 18 | 44 | - | 8 |
| Total ESALs Over Limit | 11 | 19 | - | 3 |
| **FIVE AXLE TRACTOR-SEMI** | | | | |
| Legal ESAL Limit (SDHT) | 0.396 | 1.730 | - | 1.730 |
| No. of Records Over Limit | 800 | 221 | - | 275 |
| % Records Over Limits | 39% | 11% | - | 13% |
| Avg. ESALs per Over Record | 0.515 | 2.328 | - | 2.461 |
| Sum of ESALs from Over Records | 412 | 514 | - | 677 |
| Total ESALs Over Limit | 95 | 132 | - | 201 |
| **SIX AXLE TRACTOR-SEMI** | | | | |
| Legal ESAL Limit (SDHT) | 0.396 | 1.730 | 1.660 | - |
| No. of Records Over Limit | 258 | 147 | 87 | - |
| % Records Over Limits | 26% | 15% | 9% | - |
| Avg. ESALs per Over Record | 0.508 | 2.234 | 2.243 | - |
| Sum of ESALs from Over Records | 131 | 328 | 195 | - |
| Total ESALs Over Limit | 29 | 74 | 51 | - |
| **EIGHT AXLE TRACTOR-SEMI COMBINATION UNIT** | | | | |
| Legal ESAL Limit (SDHT) | 0.396 | 1.730 | 1.410 | 1.730 |
| No. of Records Over Limit | 326 | 326 | 206 | 279 |
| % Records Over Limits | 32% | 32% | 20% | 28% |
| Avg. ESALs per Over Record | 0.486 | 2.162 | 1.783 | 2.432 |
| Sum of ESALs from Over Records | 158 | 705 | 367 | 679 |
| Total ESALs Over Limit | 29 | 141 | 77 | 196 |

**Table F.2 –Westbound Curb Lane Overweight ESALs by Vehicle Class**

| | Steering | Drive | Trailer Tridem | Trailer Tandem |
|---|---|---|---|---|
| **TWO AXLE STRAIGHT TRUCK** | | | | |
| Legal ESAL Limit (SDHT) | 1.226 | 1.570 | - | - |
| No. of Records Over Limit | 21 | 179 | - | - |
| % Records Over Limits | 2% | 15% | - | - |
| Avg. ESALs per Over Record | 3.095 | 2.682 | - | - |
| Sum of ESALs from Over Records | 65 | 480 | - | - |
| Total ESALs Over Limit | 39 | 199 | - | - |
| **THREE AXLE STRAIGHT TRUCK** | | | | |
| Legal ESAL Limit (SDHT) | 1.226 | 1.73 | - | - |
| No. of Records Over Limit | 116 | 126 | - | - |
| % Records Over Limits | 11% | 12% | - | - |
| Avg. ESALs per Over Record | 2.019 | 2.421 | - | - |
| Sum of ESALs from Over Records | 234 | 305 | - | - |
| Total ESALs Over Limit | 92 | 87 | - | - |
| **FOUR AXLE STRAIGHT TRUCK W/TANDEM STEERING** | | | | |
| Legal ESAL Limit (SDHT) | 1.296 | 2.160 | - | - |
| No. of Records Over Limit | 30 | 11 | - | - |
| % Records Over Limits | 45% | 16% | - | - |
| Avg. ESALs per Over Record | 2.308 | 3.562 | - | - |
| Sum of ESALs from Over Records | 69 | 39 | - | - |
| Total ESALs Over Limit | 30 | 15 | - | - |
| **FOUR AXLE TRACTOR-SEMI** | | | | |
| Legal ESAL Limit (SDHT) | 0.396 | 1.570 | - | 1.730 |
| No. of Records Over Limit | 9 | 12 | - | 0 |
| % Records Over Limits | 4% | 6% | - | 0% |
| Avg. ESALs per Over Record | 0.548 | 3.044 | - | 0 |
| Sum of ESALs from Over Records | 5 | 37 | - | 0 |
| Total ESALs Over Limit | 1 | 18 | - | 0 |
| **FIVE AXLE TRACTOR-SEMI** | | | | |
| Legal ESAL Limit (SDHT) | 0.396 | 1.73 | - | 1.73 |
| No. of Records Over Limit | 677 | 90 | - | 89 |
| % Records Over Limits | 44% | 6% | - | 6% |
| Avg. ESALs per Over Record | 0.540 | 2.206 | - | 2.517 |
| Sum of ESALs from Over Records | 365 | 199 | - | 224 |
| Total ESALs Over Limit | 97 | 43 | - | 70 |
| **SIX AXLE TRACTOR-SEMI** | | | | |
| Legal ESAL Limit (SDHT) | 0.396 | 1.73 | 1.66 | - |
| No. of Records Over Limit | 216 | 122 | 58 | - |
| % Records Over Limits | 31% | 17% | 8% | - |
| Avg. ESALs per Over Record | 0.538 | 2.428 | 2.097 | - |
| Sum of ESALs from Over Records | 116 | 296 | 122 | - |
| Total ESALs Over Limit | 31 | 85 | 25 | - |
| **EIGHT AXLE TRACTOR-SEMI COMBINATION UNIT** | | | | |
| Legal ESAL Limit (SDHT) | 0.396 | 1.73 | 1.41 | 1.73 |
| No. of Records Over Limit | 496 | 286 | 234 | 154 |
| % Records Over Limits | 57% | 33% | 27% | 18% |
| Avg. ESALs per Over Record | 0.539 | 2.393 | 1.905 | 2.356 |
| Sum of ESALs from Over Records | 267 | 685 | 446 | 363 |
| Total ESALs Over Limit | 71 | 190 | 116 | 96 |

APPENDIX G - PRIMARY MECHANISTIC ROAD TESTING LOCATIONS

**Figure G.1 – Local-Industrial: Portage Ave (NB), km 0.08 (June 12, 2006), PSI Inc.**

**Figure G.2 – Local-Industrial: Jasper Ave (SB), km 0.175 (June 12, 2006), PSI Inc.**

**Figure G.3 – Local-Industrial: Jasper Ave (NB), km 0.350 (June 12, 2006), PSI Inc.**

**Figure G.4 – Local-Industrial: Edson St (WB), km 0.450 (June 13, 2006), PSI Inc.**


**Figure G.5 – Local-Industrial: Idylwyld Service Rd, km 1.250 (July 27, 2006), PSI Inc.**

**Figure G.6 – Arterial: Attridge Dr (WB), km 0.100 (June 12, 2006), PSI Inc.**

**Figure G.7 – Arterial: Attridge Dr (EB), km 0.350 (July 31, 2006), PSI Inc.**

**Figure G.8 – Arterial: Attridge Dr (EB), km 1.600 (July 31, 2006), PSI Inc.**

**Figure G.9 – Arterial: Avenue C (SB), km 0.500 (July 26, 2006), PSI Inc.**

**Figure G.10 – Arterial: Preston Ave (SB), km 0.300 (July 29, 2006), PSI Inc.**

**Figure G.11 – Arterial: 8th Street East (WB), km 0.500 (August 3, 2006), PSI Inc.**

**Figure G.12 – Arterial: 8th Street East (EB), km 0.600 (August 3, 2006), PSI Inc.**

**Figure G.13 – Local & Collector: Adelaide St (WB), km 0.040 (June 13, 2006), PSI Inc.**

**Figure G.14 – Local & Collector: Kenderdine Rd (NB), km 0.200 (July 29, 2006), PSI Inc.**

**Figure G.15 – Local & Collector: Rylston Rd (WB), km 0.040 (June 13, 2006), PSI Inc.**

**Figure G.16 – Local & Collector: 31st Street (EB), km 0.075 (June 16, 2006), PSI Inc.**